AD A105073

LEVEL II

AFGL-TR-81-0031

MILITARY GEODESY AND GEOSPACE SCIENCE
Unit Four

Warren G. Heller
A. Richard LeSchack

The Analytic Sciences Corporation
One Jacob Way
Reading, Massachusetts 01867

February 1981

Scientific Report No. 8

AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AFB, MASSACHUSETTS 01731

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFGL-TR-81-0031	2. GOVT ACCESSION NO.
	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): MILITARY GEODESY AND GEOSPACE SCIENCE, Unit Four	5. TYPE OF REPORT & PERIOD COVERED: Scientific ~~Report No.~~ 8
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Warren G. Heller, A. Richard LeSchack	8. CONTRACT OR GRANT NUMBER(s): F19628-77-C-0152
9. PERFORMING ORGANIZATION NAME AND ADDRESS: The Analytic Sciences Corporation, One Jacob Way, Reading, Massachusetts 01867	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 320432AA
11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Geophysics Laboratory, Hanscom AFB, Massachusetts 01731, Monitor/Brian Mertz, Capt, USAF/LWG	12. REPORT DATE: February 1981
	13. NUMBER OF PAGES: 119
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Geodesy, gravity, physical geodesy, mapping, charting

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This lecture course provides a full-year introduction to Military Geodesy and Geospace Science. Throughout the presentation a military perspective is maintained which links Mapping, Charting, and Geodesy (MC&G) issues with modern defense requirements. Elementary preparation is assumed in the subjects of general physics, mechanics, chemistry, astronautics, and linear system theory. The student should also be familiar with differential equations, analytic geometry, and linear algebra. Some acquaintance with vector calculus is useful but not essential.

DD FORM 1 JAN 73 1473

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

The topics covered herein are intended to provide conceptual rather than working knowledge. Ideally, the student completing this course will have attained a broad understanding of the MC&G field and will be able to develop specialized expertise quickly when required.

The notes are intended to be presented in chapter/section order within each of the four Units of Instruction. However, several of the subsections in these notes contain more advanced material which may be omitted without loss of continuity. These subsections are denoted with the symbol (†) after the title. A fifth volume contains faculty material.

The organizational flow of the lectures is from concepts in the initial sections, particularly in Unit One, to applications and specific systems later on. As a result the student is often referred ahead to provide motivation in regard to relevancy. In later chapters, however, the situation is reversed with the student referred back to review important conceptual material as necessary.

FOREWORD

This lecture course provides a full-year introduction to Military Geodesy and Geospace Science. Throughout the presentation a military perspective is maintained which links Mapping, Charting, and Geodesy (MC&G) issues with modern defense requirements. Elementary preparation is assumed in the subjects of general physics, mechanics, chemistry, astronautics, and linear system theory. The student should also be familiar with differential equations, analytic geometry, and linear algebra. Some acquaintance with vector calculus is useful but not essential.

The topics covered herein are intended to provide conceptual rather than working knowledge. Ideally, the student completing this course will have attained a broad understanding of the MC&G field and will be able to develop specialized expertise quickly when required.

The notes are intended to be presented in chapter/section order within each of the four Units of Instruction. However, several of the subsections in these notes contain more advanced material which may be omitted without loss of continuity. These subsections are denoted with the symbol (†) after the title.

The organizational flow of the lectures is from concepts in the initial sections, particularly in Unit One, to applications and specific systems later on. As a result the student is often referred ahead to provide motivation in regard to relevancy. In later chapters, however, the situation is reversed with the student referred back to review important conceptual material as necessary.

GLOSSARY OF ACRONYMS AND ABBREVIATIONS FOR UNIT FOUR

ALT	Radar Altimeter	4-5
ATS-6	Applications Technology Satellite	4-4
BPSK	Biphase Modulated	4-82
C-Band	A radar frequency designation (4 to 8 GHz)	4-37
CCT	Computer Compatible Tape (LANDSAT)	4-97
ECHO	A large balloon satellite	4-3
EDIPS	EROS Data Center Image Processing System	4-95
EROS	Earth Resources Observation System	4-95
ERTS-1	Earth Resources Technology Satellite (original design for LANDSAT)	4-88
ETR	Eastern Test Range	4-37
GDOP	Geometric Dilution of Precision	4-85
GEOS-3	Geodynamics Experimental Observation Satellite	4-28
GPS	Global Positioning System (NAVSTAR)	4-2
GRAVSAT	Gravity Satellite	4-63
GSFC	Goddard Space Flight Center	4-95
HDT-P	High-Density Digital Product Tape (LANDSAT)	4-95
HOW	Handover Word	4-83
INS	Inertial Navigation System	4-85
IPF	Image Processing Facility (LANDSAT)	4-95
LAGEOS	Laser Geodynamic Satellite (launched in May 1976)	4-3
LANDSAT	A series of NASA satellites for viewing the earth at various frequencies	4-2
L-Band	A radar frequency designation (1 to 2 GHz)	4-78
LOS	Line of Sight	4-62

GLOSSARY OF ACRONYMS AND ABBREVIATIONS FOR UNIT FOUR (Continued)

MSS	Multi-Spectral Scanner (LANDSAT)	4-88
NASA	National Aeronautics and Space Administration	4-31
NAVSTAR	Alternative name for GPS (NAVigation System Using Time And Ranging)	4-2
NIMBUS-5	A meteorological satellite	4-57
NNSS	Navy Navigation Satellite System	4-2
NOSS	National Oceanic Satellite System (proposed by NASA)	4-54
PDOP	Position Dilution of Precision	4-86
PRN	Pseudorandom Noise	4-82
RBV	Return-Beam Vidicon (LANDSAT)	4-88
RMS	Root Mean Square	4-47
RSS	Root Sum of Squares	4-85
SAR	Synthetic Aperture Radar	4-5
SASS	Scatterometer System	4-5
S-Band	A radar frequency designation (2 to 4 GHz)	4-39
SEASAT	A satellite launched by NASA in 1978 for remove sensing of the earth's oceans	4-4
SKYLAB	A manned satellite program	4-31
SMMR	Scanning Multichannel Microwave Radiometer	4-5
SOM	Space Oblique Mercator Projection	4-98
SSH	Sea Surface Height	4-41
TDOP	Time Dilution of Precision	4-86
TDRSS	Tracking and Data Relay Satellite System	4-55
TLM	Telemetry Word	4-83
TOA	Time of Arrival	4-79

GLOSSARY OF ACRONYMS AND ABBREVIATIONS FOR UNIT FOUR (Continued)

TT&C	Tracking, Telemetry, and Command	4-6
UHF	Ultra-High Frequency (300 to 3000 MHz)	4-10
USGS	United States Geological Survey	4-95
USDA	U. S. Department of Agriculture	4-94
UTM	Universal Transverse Mercator Projection	4-98
VHF	Very High Frequency (30 to 300 MHz)	4-6
VIRR	Visible and Infrared Radiometer	4-5

UNIT FOUR

TABLE OF CONTENTS

UNIT FOUR

TABLE OF CONTENTS (Continued)

UNIT FOUR

LIST OF FIGURES

UNIT FOUR

LIST OF FIGURES (Continued)

UNIT FOUR

LIST OF TABLES

UNIT FOUR

SATELLITE SYSTEMS

CHAPTER ONE
INTRODUCTION

Unit Four considers satellite systems, used primarily for

- Reconnaissance and information gathering
- Navigation and positioning
- Obtaining geodetic and geophysical data.

The categories overlap since information of geodetic and geophysical value is often obtained as a by-product of the tracking of satellites. Such data may even be provided by satellites launched for other purposes.

Chapters Two through Five of this Unit review information pertinent to all satellite systems. The topics covered are:

- Platform considerations
- Gravitational perturbation effects on satellites
- Attitude reference systems
- Satellite tracking and positioning.

Then three different examples of operational satellite systems are reviewed in detail, with the first two dedicated to navigation and geodetic positioning, and the third to LANDSAT. Chapters Six and Seven cover

- Navy Navigation Satellite System (NNSS)
- Global Positioning System (NAVSTAR GPS).

The third example, LANDSAT, originally called the Earth Resources Technology Satellite, employs several types of imaging sensors for a wide variety of applications, including

- Study of erosion patterns
- Flood prediction and damage assessment
- Urban planning
- Drought and irrigation studies
- Detection of sea ice hazards in shipping lanes.

CHAPTER TWO

SATELLITE PLATFORM CONSIDERATIONS

4.2.1 Introduction

This section discusses a number of the fundamental factors in satellite systems design. Although satellites are designed for many purposes, there are common factors that must be considered in the design of essentially all satellites*. The most important of these are

- Environmental Factors - Satellites must operate in a near-vacuum, zero-gravity environment, in the presence of wide temperature changes and high radiation levels. These factors have significant influences on the design of operational satellites.

- Tracking, Telemetry, Command, Data Processing - All satellites require communications systems to provide a two-way radio link with ground control stations. To aid ground stations in tracking the satellites, devices called beacons or transponders are placed on board to transmit signals to ground-based tracking systems. A further part of the necessary communication involves telemetry data, to permit scientists and engineers at the ground stations to monitor the status of the spacecraft and to receive the data measured by the spacecraft instruments. Another part of the communications function enables the satellite to receive

---

*Those satellites that are designed exclusively as passive reflectors (e.g., ECHO, LAGEOS), whose sole function is to reflect signals transmitted from one ground station to another, are not included in this discussion. However, such satellites are relatively few in number.

commands from the ground stations. The commands serve purposes such as to direct the satellite to execute maneuvers, to begin or to end experiments, or to change its status in some other way. Satellites often carry computers and tape recorders to allow onboard processing and storage of data for future transmission to ground stations.

- Power Systems - Most satellites operate under solar power. These satellites carry solar cells which collect energy from the sun and recharge batteries carried on board the spacecraft. The power system is used to supply energy for operating all of the satellite's equipment. Other satellites use nuclear power developed from small onboard generators.

- Satellite Sensors - Many satellites carry sensing equipment of various types. These sensors are discussed in many of the chapters in this unit. Most currently used sensors operate at microwave, infrared, or optical frequencies. These frequencies are high enough to allow the measurement of phenomena on the earth's surface or in the atmosphere. Time-varying ionospheric and atmospheric effects sometimes limit sensor operation, but an effective systems design will, in most circumstances, enable a satellite to overcome these difficulties.

Satellites also contain systems for attitude control and orbit adjustments. These are described later.

Figures 4.2-1 and 4.2-2 illustrate various spacecraft systems for two recent satellites, SEASAT-1 and ATS-6. These two satellites are used for specific illustrations in the following sections.

SEASAT-1 was an oceanographic satellite designed to demonstrate remote sensing of the ocean using microwave sensors. SEASAT, which was solar-powered, carried a Doppler beacon, a

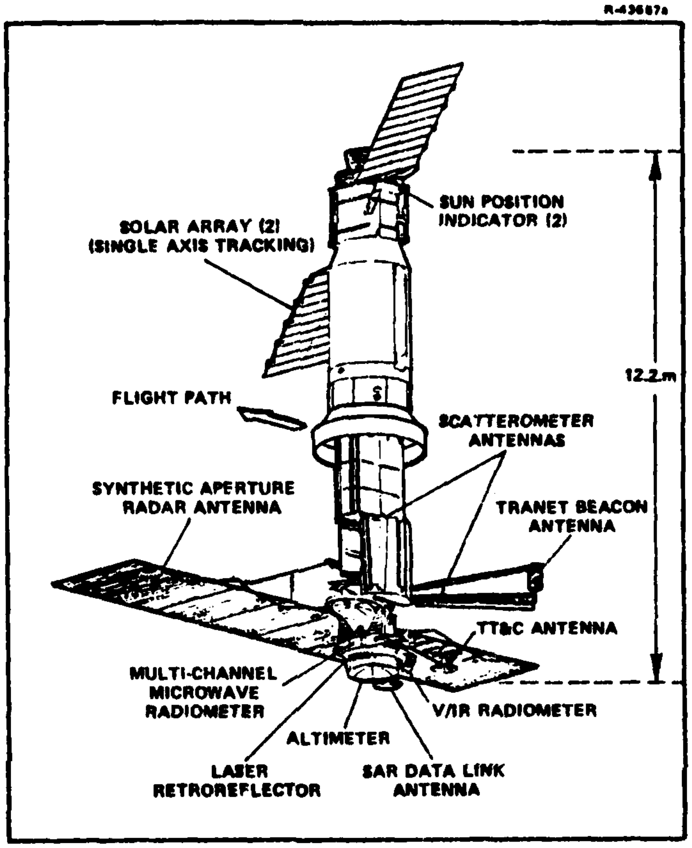


Figure 4.2-1 The SEASAT Satellite in Orbit Configuration

unified S-band transponder, laser reflectors for tracking by ground stations, and five microwave sensors. These sensors were a radar altimeter (ALT) for sea surface topography (used for ocean geoid, gravity, and ocean current mapping), a synthetic aperture radar (SAR) for imaging studies, the SEASAT-A* scatterometer system (SASS) for ocean wind and wave measurements, a scanning multichannel microwave radiometer (SMMR) for passive microwave imaging, and a visible and infrared radiometer (VIRR)

*SEASAT was referred to as "A" before orbital deployment. The designation was changed to "1" once operational status had been achieved.

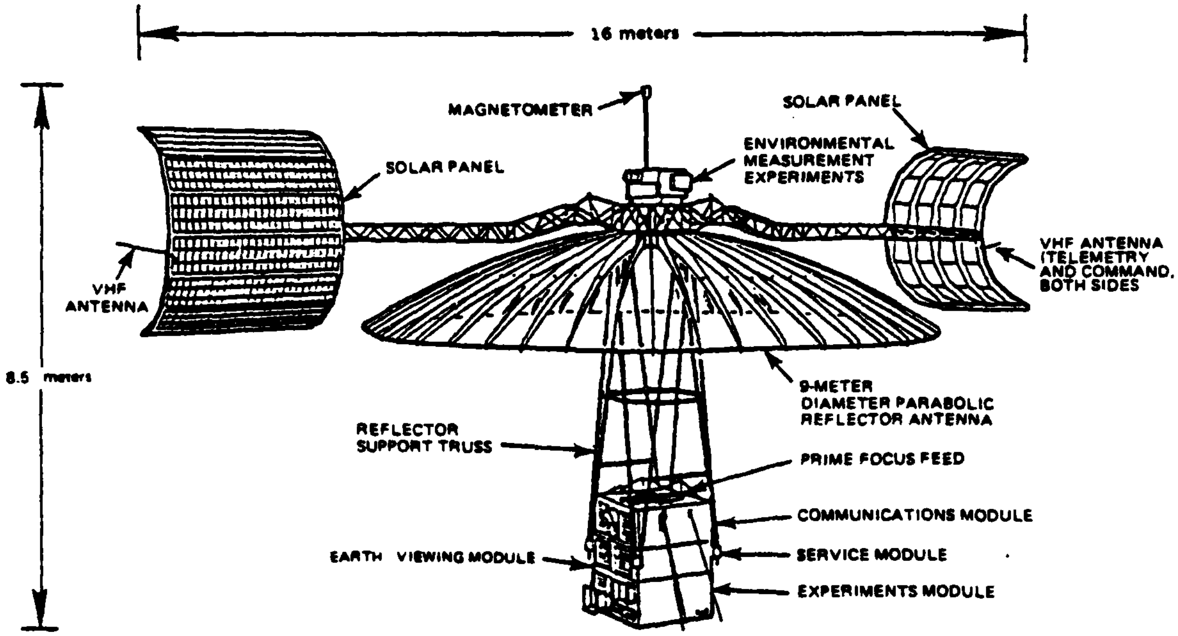


Figure 4.2-2 Orbital Configuration for ATS-6

for passive imaging at optical and infrared wavelengths. The tracking, telemetry, and command (TT&C) antennas provide for communications with ground stations.

The Applications Technology Satellite (ATS-6) was the final vehicle in a series of experimental advanced-technology satellites designed for operation in equatorial geosynchronous orbits. ATS-6 contained a number of communications and remote sensing experiments. A geodetic experiment, satellite-to-satellite tracking for gravity determination, is discussed in Chapter Five (Section 4.5.3). ATS-6 was also solar-powered and performed communications and tracking in the Very High Frequency (VHF) band.

4.2.2 Environmental Factors

Vacuum and Radiation - Satellites operate in a nearly perfect vacuum. The space environment does, however, include a small atmospheric density (especially for satellites below 200 to 300 km altitude) which can produce a significant frictional drag force on the satellite. Over a period of time this force will decrease the average orbital altitude and eventually cause the spacecraft to reenter the atmosphere.

The satellite environment also includes micrometeoroids, which can strike the satellite at high velocity. Most satellites carry shielding to protect sensitive electronic instruments from micrometeoroid impacts. There is also significant radiation from solar flares, cosmic rays, and charged particles moving within the earth's magnetic field. Because this radiation can adversely affect the electronics on board the spacecraft, there is a requirement for shielding and special radiation-resistant design.

For unmanned satellites, there is no need to pressurize the spacecraft to supply an atmosphere. The electronic instruments will operate in a near-vacuum. It is, however, necessary to allow the atmosphere that was present in the satellite before launch to escape (to be vented) into space so that the partial pressure of atmospheric gasses within the satellite will not cause short circuits in the spacecraft electronic equipment.

Gravity - A satellite in orbit about the earth is in free fall. Thus, the center of mass of the satellite experiences no acceleration due to gravity. However, for large spacecraft, there is a significant change in gravitational acceleration across the body of the spacecraft. This change in the

gravitational acceleration is due to the <u>gradient</u> of the earth's gravity field. Gravity gradients can be used to stabilize the spacecraft in orbit. This topic is discussed further in Chapter Four (Section 4.4.3), under the heading <u>attitude control systems</u>.

<u>Temperature</u> - Temperature control on board a satellite can be very important. Most electronic equipment can operate only within a relatively narrow band of temperatures. Thus, special techniques are required to maintain a reasonably stable temperature inside the spacecraft.

In a vacuum, there is no convection cooling. Thus, heat generated by the operation of electronic equipment must be dissipated using other techniques. Generally, conducting metal strips are employed to act as <u>heat sinks</u> for removing heat from electronic equipment.

Most spacecraft systems carry heaters in order to prevent the temperature from becoming too low. Heat can be supplied directly to equipment to maintain a satisfactory operating temperature. Spacecraft heating systems are usually called upon to deliver heat during those periods when the satellite is in the earth's shadow. Finally, the surface of the spacecraft is covered with special reflecting paints that are designed to prevent direct solar radiation from heating the spacecraft to an unacceptably high temperature.

4.2.3 Tracking, Telemetry, Command, and Data Processing

Communications between the satellite and ground stations are required for a number of purposes. Among these are the following:

- To provide signals for spacecraft tracking - Many satellites carry devices on board to aid ground-based tracking systems. One type of device, a Doppler beacon, broadcasts a signal from the satellite to the ground for tracking. Another such device, a transponder, receives a signal from the ground, shifts (transponds) the signal to another frequency to avoid interference, and retransmits the signal to the ground tracking systems.

- To monitor the status of the spacecraft - Data measured on board the spacecraft concerning temperature, available power, equipment voltage and current readings, etc. are required in order for ground station controllers to be sure that the spacecraft is operating within acceptable limits.

- To receive scientific and engineering data - The measurements made by the instruments on board the spacecraft must be communicated to the ground station for analysis. Although some direct on-board processing can be performed by a spacecraft computer system, most of the detailed data analysis is performed by scientists and engineers who receive the data transmitted by the spacecraft. The scientific and engineering data, along with the status-monitoring data, are often called telemetry.

- To command the spacecraft - Periodically during a satellite mission, it is necessary for ground controllers to direct the spacecraft to perform various actions. These may include functions as simple as turning equipment on or off, or more complex activities such as maneuvering the spacecraft to attain a new orbit, or to modify an experiment currently in progress. In order to do this, it is necessary for the ground station to be able to transmit command data to the spacecraft. Generally, there is a system of command verification which allows the ground controllers to verify that the

spacecraft has received the command instruction properly before executing the command.

To accomplish these functions, special spacecraft communications systems have been designed. Generally, these operate in the microwave frequency region (1 GHz to 6 GHz) although, as noted earlier, some systems (for example, ATS-6) operated in the VHF or UHF frequency bands (typically from 100 MHz to 500 MHz). Spacecraft communications systems include specially designed antennas, receiving and transmitting equipment, and interface units connecting the communications system to other spacecraft systems. Examples of these are shown in Figs. 4.2-1 and 4.2-2.

Communications can be performed in either digital or analog modes. Digital data are customarily derived from the scientific and engineering experiments. These data have generally been digitized by analog/digital converters prior to transmission. Analog communication is still employed in a number of satellites for specific applications. Voice relay in communication satellites may be performed using analog circuits and certain very high data-rate requirements (e.g., the SEASAT synthetic aperture radar at 100 MHz) are met with analog techniques.

4.2.4 Spacecraft Power Systems

Generally, satellites are powered using solar energy systems. These systems derive their energy from large solar arrays (as illustrated in Figs. 4.2-1 and 4.2-2). The arrays are comprised of semiconductors which convert the sun's energy into electricity that is stored in a battery. Most systems use nickel-cadmium batteries for energy storage. The spacecraft power system is designed to supply required voltages and currents to the various spacecraft systems.

A spacecraft operates on battery power during launch, during most parts of an orbit in which the satellite is in the shadow of the earth, and during certain peak-loading conditions. The batteries are recharged whenever solar arrays are producing more power than the spacecraft is consuming. A satellite's power supplies are usually controlled and monitored from the ground through the satellite's command and telemetry systems.

Certain spacecraft use nuclear power sources. Some mission requirements can only be met in this way. For example, the recent Saturn probe was too far from the sun to be solar powered. However, most earth-orbiting U.S. satellites use solar power.

4.2.5 Spacecraft Sensors

Spacecraft sensors have included instrumentation for a tremendous variety of experiments over the last two decades. Among these sensors are equipment for measuring the earth's radiation field, gravity field, magnetic field, oceanographic phenomena, and many other quantities. Satellite sensors may be divided into two principal categories, active and passive.

The active sensors transmit signals from the spacecraft to the earth's surface. This is often in the form of a radar signal emitted from the satellite to the earth's surface and reflected back to the satellite. Spacecraft radars have been designed to measure variations in the ocean surface and the weather, and to provide data from which variations in the earth's gravity field can be deduced. Examples of spacecraft radar systems are the SEASAT altimeter and synthetic aperture radar described earlier.

Passive sensors involve no transmission from the satellite, but measure energy radiated or reflected from the surface of the earth. A simple example of a passive sensor is a camera, which is used to produce images at optical frequencies. Other examples include the imagery produced by the SEASAT microwave, visible spectrum, and infrared radiometers shown in Fig. 4.2-1.

In addition to remote sensing equipment, spacecraft systems serve a wide variety of other functions including navigation and communication. Some of these applications are discussed later.

CHAPTER 3

GRAVITATIONAL PERTURBATION EFFECTS ON SATELLITES(†)

In order to make effective use of the data collected by satellite-based sensors, or to employ satellites in navigation systems, it is necessary to know satellite position (and often velocity as well) to a high degree of precision. In principle this requirement would be satisfied if satellite position and velocity were expressible as a function of time, in the form:

$$\underline{x} = \underline{f}(t;\alpha_i;\beta_i) \tag{4.3-1}$$

where

- $\underline{x}$ is the six-element vector (called the <u>state vector</u>) of position and velocity components
- t is time
- α_i are parameters characterizing the orbit of the satellite
- β_i are parameters related to the forces acting on the satellite

For example, the β_i parameters would include the C and S coefficients characterizing the earth's gravitational field (see Section 1.3.2 of Unit One). Also included are constants associated with other forces acting on the satellite such as:

- Lunar and solar gravitational attraction
- Atmospheric drag
- Solar radiation pressure.

---

†This chapter contains material at a more advanced level than the rest of the text.

For realistic force models it is not possible, in practice, to solve the equations of motion in closed form; thus an expression having the form of Eq. (4.3-1) cannot actually be written down. Instead, approximation methods of various kinds must be used to come as close as is required to the true (but unattainable) ideal solution expressed by Eq. (4.3-1).

One widely used approach is to begin by neglecting all forces other than the gravitational attraction of the earth, and to approximate this force by a simple inverse-square law, as though the earth were a point mass or a sphere of uniform density. This is equivalent to setting all the C and S coefficients of the geopotential (see Eq. 1.3-12 of Section 1.3.2, Unit One) to zero except for

$$C_{00} = 1 \tag{4.3-2}$$

Under these assumptions, the satellite would move according to Kepler's Laws in an elliptic orbit with the center of the earth at one focus. (The reader may find it helpful to review Keplerian motion concepts from a text on mechanics or astrodynamics.) The orbit is defined by six parameters called orbital elements, which are constants.

Because the neglected forces are generally very small when compared with the inverse-square force, the effect of including them is to perturb, or change slightly, the orbit that would be predicted on the basis of point-mass gravitation alone. A very effective way of doing this is to retain the concept of Keplerian motion, but to regard the orbital elements not as constants, but as quantities that are changing slightly (being perturbed) as a function of time. For example, using the classical orbital elements (illustrated in Fig. 4.3-1), the effect of the perturbations can be expressed in the form of six equations (called the Lagrange planetary equations):

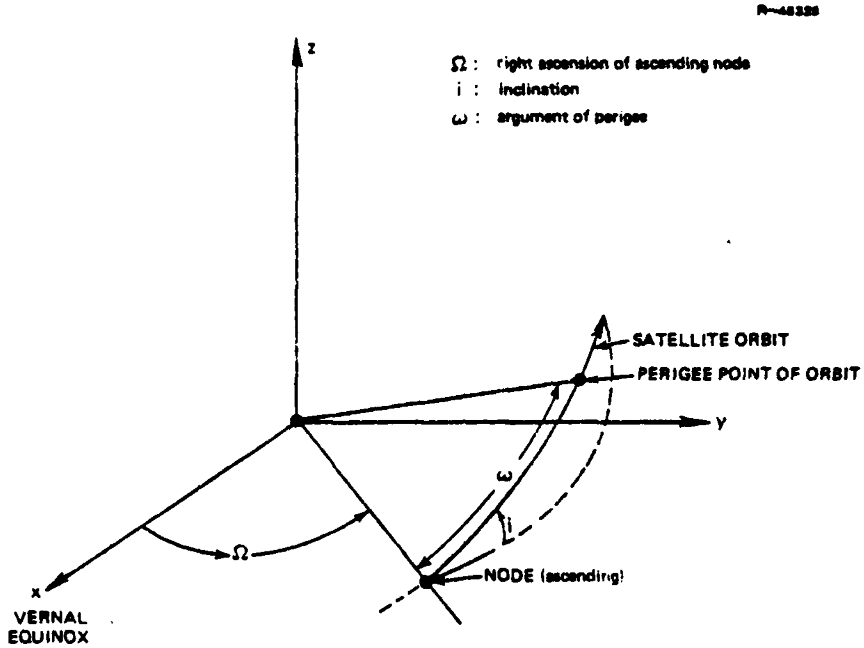


Figure 4.3-1a Classical Orbital Elements - Orientation Elements

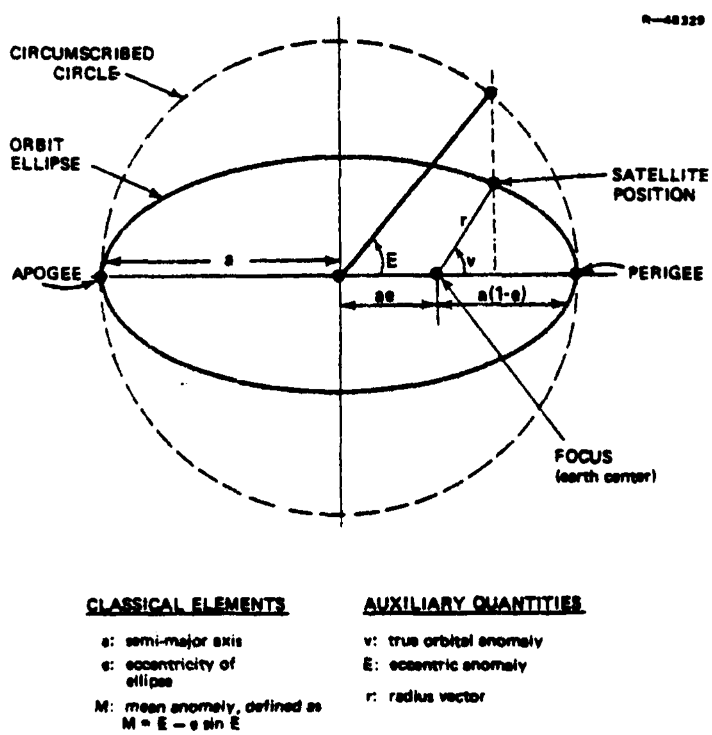


Figure 4.3-1b Classical Orbital Elements - Elements Defined in the Plane of the Orbit

$$\frac{da}{dt} = f_1(a,e,\omega,i,\Omega,M;F) \tag{4.3-3}$$

$$\frac{de}{dt} = f_2(a,e,\omega,i,\Omega,M;F) \tag{4.3-4}$$

$$\frac{d\omega}{dt} = f_3(a,e,\omega,i,\Omega,M;F) \tag{4.3-5}$$

$$\frac{di}{dt} = f_4(a,e,\omega,i,\Omega,M;F) \tag{4.3-6}$$

$$\frac{d\Omega}{dt} = f_5(a,e,\omega,i,\Omega,M;F) \tag{4.3-7}$$

$$\frac{dM}{dt} = f_6(a,e,\omega,i,\Omega,M;F) \tag{4.3-8}$$

where each of the right side expressions is a function of the orbital elements and of the perturbing force, F. For instance,

$$f_1 = 2 \left(\frac{a}{\mu}\right)^{1/2} \frac{\partial F}{\partial M} \tag{4.3-9}$$

a form that is convenient if the perturbing force can easily be expressed as a function of the orbital elements, or

$$f_1 = \frac{a^{3/2}}{\mu^{1/2}\,(1-e^2)^{1/2}} \left[A\ e \sin v + B\ \frac{a(1-e^2)}{r}\right] \tag{4.3-10}$$

a form that is preferred if the perturbing force, F, can be resolved into a <u>radial component</u>, A, and an <u>along-track component</u>, B, as shown in Fig. 4.3-2. (The cross-track component, C, appears in the expressions for f_4 and f_5 only.) In Eqs. (4.3-9) and (4.3-10),

a,e,M are defined in Fig. 4.3-1

v is the <u>true anomaly</u> (Fig. 4.3-1)

r is the <u>radius vector</u> (Fig. 4.3-1)

μ is the geocentric gravitational constant (equivalent to GM, as listed in Table 1.3-2, Section 1.3.2, Unit One)

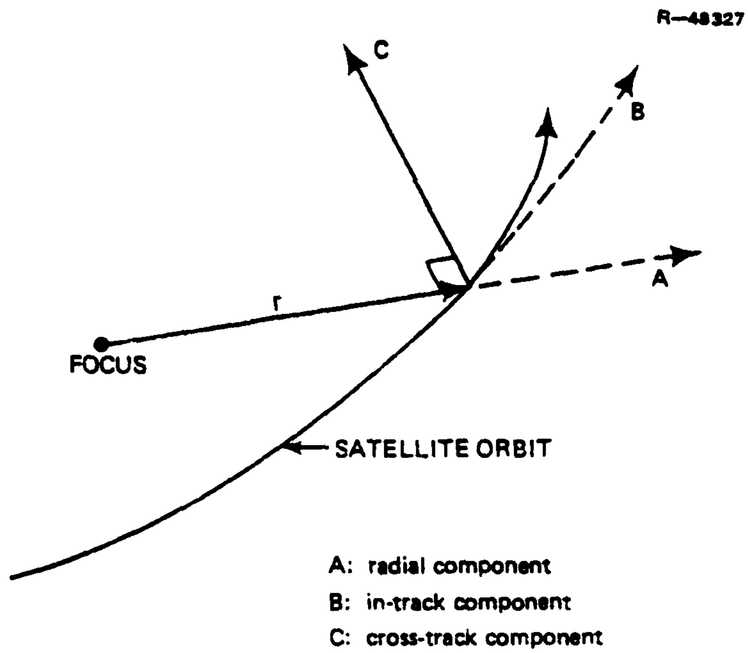


Figure 4.3-2   Components of the Perturbing Force

Since the perturbations are additive (principle of superposition), F may be regarded as the vector sum of individual perturbing forces:

$$F = \sum_i F_i \tag{4.3-11}$$

and the effects on the orbital elements can be considered individually, and then summed. For example,

$$\frac{da}{dt} = \sum_i \left(\frac{da}{dt}\right)_i \tag{4.3-12}$$

$$a(t') = a_o + \sum_i \int_o^{t'} \left(\frac{da}{dt}\right)_i dt \tag{4.3-13}$$

where

$(\frac{da}{dt})_i$ is the perturbation induced by the i^{th} perturbing force

$a(t')$ is the semi-major axis at a particular time t'

a_o is the original (unperturbed) semi-major axis at time 0

At any desired level of accuracy, only those perturbations need be considered that are significant at that accuracy level.

The remainder of this chapter will focus attention on gravitational perturbations -- those resulting from the effects of C and S coefficients of the geopotential (Eq. 1.3-12, Unit One) other than C_{00}.

Gravitational perturbations are dominated by the effect of C_{20} (related to the oblateness of the earth), since this coefficient is approximately 1000 times larger than the other C and S terms. As a first approximation, the effects of C_{20} are classified as shown in Table 4.3-1.

Since the periodic perturbations (affecting all the elements) are bounded and generally very small in amplitude, the major effect is the secular perturbation, which affects only the angular elements ω, Ω, and M. The change in ω is called the precession of perigee:

$$\omega(t) = \omega_o + (\dot{\omega})t \quad (4.3\text{-}14)$$

$$\dot{\omega} = (4.98)a^{-7/2} (1-e^2)^{-2} (5 \cos^2 i - 1) \text{ deg/day} \quad (4.3\text{-}15)$$

TABLE 4.3-1

FIRST-ORDER PERTURBATIONS DUE TO C_{20}

TYPE OF PERTURBATION	DESCRIPTION
Secular	Changes linearly with time
Short-Periodic	Period equal to satellite orbital period and sub-multiples thereof
Long-Periodic	Period equal to integral multiples of the time required for a complete cycle of ω (see Eq. 4.3-14)

It can amount to as much as 20 deg/day for a low altitude satellite in a circular equatorial orbit. The second secular effect is called the regression of the node:

$$\Omega(t) = \Omega_o + (\dot{\Omega})t \qquad (4.3\text{-}16)$$

$$\dot{\Omega} = -(9.96)a^{-7/2}\,(1-e^2)^{-2}\cos i \text{ deg/day} \qquad (4.3\text{-}17)$$

Nodal regression rates approach 10 deg/day for a close satellite with small inclination. The third effect is a change in the period of the satellite that can be as much as six to eight seconds. In Eqs. (4.3-15) and (4.3-17), the semi-major axis, a, is measured in units of the earth's equatorial radius (see Section 1.2.1 of Unit One), while the dot above a symbol indicates a derivative with respect to time.

Inclusion of additional geopotential terms gives rise to small modifications of the secular perturbations, and to small periodic terms that have frequencies corresponding to

- The orbital frequency
- The perigee precession frequency
- The earth's daily rotation rate

and sums and differences of multiples of the above frequencies. Computations that strive for very high accuracy require the inclusion of thousands of small periodic terms and substantial computer time.

There is one important situation in which geopotential terms other than C_{20} can have a major perturbative effect on the orbit of a satellite. If there is a <u>commensurability</u> between the satellite's orbital period and the rotation of the earth, leading to a repeating ground track, then the effect of certain geopotential terms will tend to be cumulative, rather than periodic, and large perturbations will gradually build up. This condition is known as <u>resonance</u>. Two examples are cited. Geostationary (24-hour) satellites, used -- for example -- as communication relays, are especially sensitive to the C_{22} and S_{22} terms of the geopotential. The resulting resonance causes the satellite to drift away from its nominal stationary point. Fuel must be expended from time to time (<u>station keeping</u>) to return the satellite to the desired location. The second example of resonance occurs for a nearly circular orbit with a semi-major axis

$$a = 1.1958 \text{ earth radii} \tag{4.3-18}$$

corresponding to a height above the earth of about 1250 km (period of about 110.5 min), which has a 13 to 1 commensurability with the earth's rotation. Resonance is caused by geopotential coefficients (C_{nm} or S_{nm}) with

$$m = 13 \tag{4.3-19}$$

principally $C_{13,13}$, $S_{13,13}$, $C_{15,13}$, $S_{15,13}$, $C_{17,13}$, and $S_{17,13}$. Ultimately, this form of resonance will change the orbital period and the semi-major axis until the commensurability condition is no longer met.

CHAPTER FOUR
ATTITUDE REFERENCE AND ORBITAL CONTROL SYSTEMS

4.4.1. Introduction to Attitude Reference Systems

The attitude of a spacecraft is its angular orientation in space relative to a defined coordinate system. This should be distinguished from the position of its center of mass relative to a coordinate system that does not necessarily coincide with the system used for attitude. Although position is usually expressed in an inertial coordinate system, many satellite systems require attitude in terms of the local vertical, using horizon sensors or gravity-gradient stabilization to establish the orientation of the vertical.

This section discusses methods of measuring the attitude of the spacecraft using devices called attitude sensors. Two other related concepts are discussed. The first of these is called attitude determination. This is the process of analyzing data collected from attitude sensors, processing these data, and computing the attitude of the spacecraft at a given time.

The second concept is that of attitude control. Attitude control is the process of attaining a desired spacecraft angular orientation. Attitude control is usually divided into two principal aspects. The first of these is attitude maneuvering wherein the attitude of the spacecraft is changed from one condition to a desired second condition. The second of these is attitude stabilization in which a desired attitude for the spacecraft is maintained over a given interval of time.

There are two principal classes of spacecraft stabilization methods. The first of these is spin-stabilization. Spin-stabilized spacecraft are rotated about a selected spacecraft axis. The spacecraft angular momentum is approximately fixed in the direction of the spin-axis over a period of time. This will ultimately be affected by external torques that are applied to the spacecraft by the orbital environment.

The second major stabilization category is that of three-axis stabilization. Three-axis stabilized satellites are controlled in all three directions of a spacecraft-centered coordinate system. A spacecraft so controlled may be pointed in a fixed direction in inertial space or controlled to maintain a fixed orientation relative to the surface of the earth.

There are a number of reasons for determining and controlling the attitude of a spacecraft. These include the following:

- Spacecraft orientation for maneuvering - On occasion it is necessary to orient the spacecraft in order to align it properly for orbit maneuvers
- Antenna and spacecraft sensor pointing - In order to direct the antenna of the spacecraft or a remote sensing device in the proper direction for operation, it is necessary to know the angular orientation of the satellite in space
- Data interpretation - In order to understand the measurements that are collected by certain spacecraft sensors it is necessary to know the orientation of the spacecraft. For example, spacecraft magnetometers can be designed to collect data defining the three components of the geomagnetic field if the spacecraft orientation is known to sufficient accuracy.

Attitude determination and control accuracy requirements range from approximately one degree for applications such as antenna pointing to a few arcseconds for certain data interpretation needs. To meet accuracies over this range a number of techniques for attitude measurement and data processing have been developed. These techniques and data processing algorithms are described in the next section.

4.4.2 Attitude Sensors and Attitude Determination

Sun Sensors - The direction of the sun relative to the spacecraft coordinate system provides a convenient attitude reference source. Sun sensors are the most common type of attitude sensor for satellite applications. They are relatively simple and reliable devices because the sun is extremely bright and has a relatively small angular radius (approximately 0.25 deg) when viewed from an earth-orbiting satellite.

Sun sensors have other applications in addition to attitude determination. They used, for example, to orient solar power arrays and to prevent sensitive spacecraft equipment from being pointed at the sun. Deployed on either spin-stabilized or three-axis stabilized spacecraft, sun sensors can be combined with other types of attitude sensors to provide an extended overall attitude determination and control capability.

Horizon Sensors - A second type of attitude sensor that has been important for many applications is the horizon sensor. Horizon sensors detect the earth's horizon relative to the spacecraft coordinate system. They are particularly important for earth-oriented satellites such as LANDSAT, SEASAT, and communication satellites. It is necessary to detect the horizon of the earth rather than just the earth itself, because the earth is an extended object when viewed by orbiting satellites.

Using the entire planet as an angle reference would provide too ambiguous a measurement.

Horizon detectors are generally infrared devices, sensitive to the difference between the infrared radiation emitted by the earth and the relative lack of infrared radiation in space. By determining the edge of the detected radiation field it is possible to measure the orientation of the satellite relative to the earth's horizon. One difficulty with earth horizon sensors is the fact that the earth's horizon is not precisely defined, because of atmospheric radiation and refraction. This limits the accuracy of horizon sensors relative to other techniques. However, for many applications requiring accuracies of only 0.5 to 1 deg, horizon sensors are satisfactory. They are relatively simple and lightweight compared to more accurate systems.

<u>Magnetometers</u> - Magnetometers carried on board the spacecraft are used to measure the direction of the earth's magnetic field relative to the spacecraft. From a knowledge of the orientation of the earth's magnetic field, the spacecraft attitude can be determined. Magnetometers are also relatively simple and lightweight attitude sensors. However, because of uncertainties in current determinations of the earth's magnetic field, they do not provide high accuracy. Furthermore, they cannot operate satisfactorily at high altitudes, because the earth's magnetic field attenuates with increasing altitude. Generally it is impossible to obtain satisfactory attitude measurements using magnetometers at altitudes above 6000 km.

<u>Star Sensors</u> - The most accurate attitude sensors are <u>star sensors</u> which measure the direction to known stars relative to the spacecraft coordinate system. Generally, a star catalogue is maintained in the spacecraft computer and star

directions are computed from the star catalogue. The attitude of the spacecraft is determined by comparing the computed directions with directions inferred from the measuring equipment. A large number of stars is usually contained in the catalogue so that occultation and interference from such bright sources as the sun and the earth need not be significant limitations. A more detailed description of star sensors is given in Section 2.3.7 of Unit Two.

As compared with magnetometers and horizon sensors, star sensors are very complex and expensive devices. Their physical requirements in terms of space and power are also greater than those of other attitude sensors. However, when high accuracy is required, star sensors are mandatory. With star sensors, the attitude of a spacecraft can be determined to within a few arcseconds.

Gyroscopes - Inertial reference systems are also used to measure changes in the attitude of a spacecraft. Since the fundamentals of inertial navigation are discussed elsewhere (Chapter Three of Unit Two), a detailed treatment is not provided here. Instead, a brief description of spacecraft gyro types is given.

Three basic types of gyroscopes are used on board spacecraft for attitude determination/control purposes.

- Rate gyros
- Rate integrating gyros
- Control moment gyros.

Rate gyros measure spacecraft angular rates and are used in combination with a feedback control system to regulate spin rate and to perform attitude stabilization. Rate integrating gyros measure changes in spacecraft angular orientation.

Specifically, they measure an incremental rotation in spacecraft attitude over a small time interval and integrate these incremental rotations to produce an accurate measure of the total attitude displacement. Rate integrating gyros are generally much more accurate than rate gyros. However, they are also more complex and expensive.

Control moment gyros are, strictly speaking, not attitude sensors at all. They are used to generate attitude control torques in response to commands from ground controllers. These torques are effected by producing gimbal rotation and changing a spin-axis orientation. Control moment gyros are used on board very large spacecraft only.

Attitude Determination - As stated earlier, attitude determination is the process of computing spacecraft attitude from onboard attitude sensors. Most spacecraft carry a combination of attitude sensors in order to combine the relative advantages in an overall attitude determination/control system.

For example, the ATS-6 spacecraft, described in Chapter Two, employed infrared earth horizon sensors, digital sun sensors, a star tracker designed to view the North star (Polaris Tracker), and an inertial reference assembly based on gyroscopic technology. Combined with the attitude control system, the sensors permitted spacecraft pointing accuracies of 0.1 deg.

As another example, the SEASAT spacecraft, described in Chapter Two, contained two infrared earth horizon sensors, a digital sun sensor system, and magnetometers to measure attitude relative to the earth's magnetic field. Note that the SEASAT orbit was at a relatively low altitude (approximately 800 km). Thus, a magnetometer system was feasible for SEASAT, while the ATS-6 spacecraft, at a synchronous altitude of

40,000 km, was much too high to employ a magnetometer attitude reference system.

Current attitude determination algorithms are based on the application of statistical models and least-squares or Kalman filtering techniques to process attitude sensor data. The data produced by attitude sensors may take on several forms. For example, a sun sensor produces an event time at which the sensor axis is oriented directly toward the sun. On the other hand, a horizon sensor will produce a measure of the central body width, which is the angular arc subtended by the earth. The system measures horizon crossing times and the interval between the "in-crossing" and "out-crossing" in order to produce the central body width measurement. Magnetometers measure angular orientation of the spacecraft relative to the earth's magnetic field. Star sensors, depending on type, provide event time measurements (Fig. 2.3-26, *Unit Two*) or spacecraft angular orientation measurements relative to the stars in the star catalogue.

4.4.3 Attitude Control Systems

There are two general categories of attitude control systems, passive and active. Passive attitude control systems employ torques produced by the spacecraft environment to maintain the spacecraft attitude. An example is the gravity-gradient attitude control system based on the fact that the gravity field of the earth changes over the length of the spacecraft. These changes are large enough to stabilize the spacecraft for specially designed elongated satellites. Generally, a massive spacecraft boom is employed to achieve this type of stabilization. A gravity-gradient system was employed on board the GEOS-3 spacecraft as shown in Fig. 4.4-1. Other types of passive attitude control systems include solar sails which collect

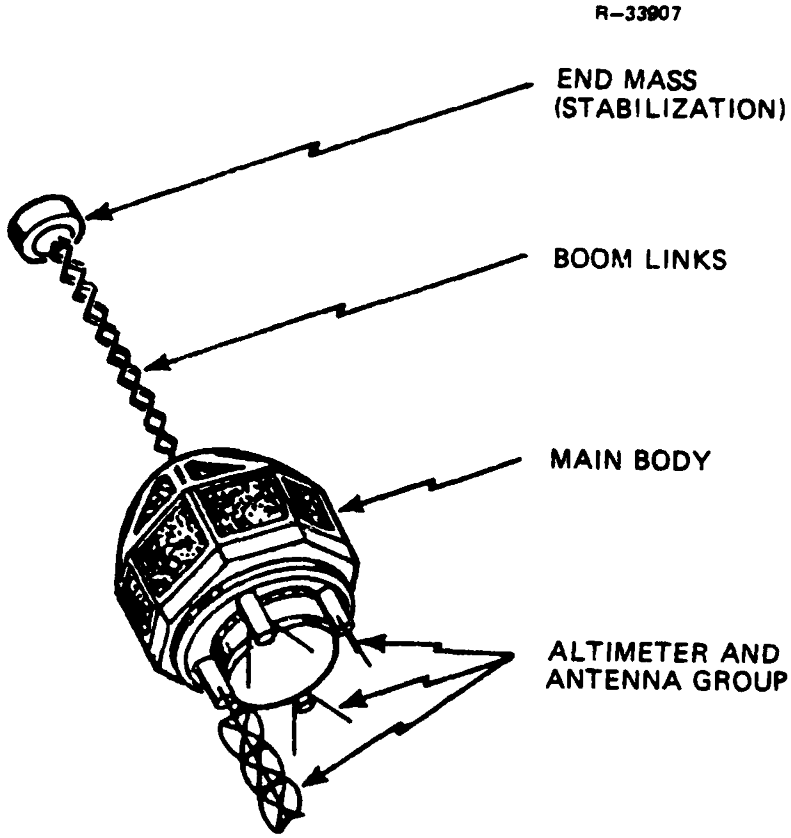


Figure 4.4-1 GEOS-3 Satellite, Showing Gravity Gradient Stabilization

solar radiation and produce torques to orient the spacecraft in the desired direction.

A common form of active control system is based on gas jets. These are simple rocket systems that expel gas in order to produce torques for orienting a spacecraft. Other types of active attitude control systems include electromagnetic control systems, which produce torques by passing currents through wires which are acted upon by the earth's magnetic field. These torques can be used to orient the spacecraft in any desired direction.

4.4.4 Orbit Control Systems

Orbit control systems are designed to change the spacecraft orbit, or to maintain a spacecraft in a desired orbit despite the effects of perturbing forces.

The orbit of a spacecraft may need to be changed occasionally in order to accomplish its mission. For example, ATS-6 was a synchronous spacecraft that maintained a nearly fixed position over the earth's equator. However, the longitude of this fixed position needed to be changed from time to time in order to accomplish desired mission functions. Thus, the spacecraft was maneuvered by an onboard gas thrusting system to position it at various longitudes during the mission. ATS-6 was positioned over regions in the Pacific for satellite-to-satellite tracking experiments, over the Indian Ocean for an educational television experiment, and over the Atlantic for spacecraft commmunication.

SEASAT was maneuvered at various times during its mission to place the spacecraft into different types of desired orbits. For example, one type of spacecraft orbit was designed specifically to cause SEASAT to pass over a calibration station located at Bermuda to calibrate the spacecraft radar altimeter. The orbit was designed to repeat the same ground track every three days during the calibration period. This maneuvering was also produced by an onboard orbit control system.

4.4.5 Summary of Attitude Reference and Orbit Control Systems

There is an important connection between attitude and orbit systems. It has already been mentioned that one of the functions of an attitude reference system is to orient the spacecraft in a desired direction in order to maneuver the

spacecraft into a new orbit. Another important relationship between attitude reference and orbit control systems is the coupling of attitude orientation and orbit perturbations. One example of this is the orbit perturbation produced by atmospheric drag. Atmospheric drag is the friction on the spacecraft produced by the vestiges of the earth's atmosphere at orbital altitude. For relatively low-altitude satellites this can be a significant effect. The drag is proportional to the cross section of the spacecraft as it moves through the earth's atmosphere. Depending on spacecraft orientation, the amount of atmospheric drag can be significantly altered. A recent example of this type of maneuvering was the attempt by NASA ground controllers to orient SKYLAB to vary the atmospheric drag on the spacecraft, in order to maneuver it during the final stages of its descent. Commands were sent to SKYLAB to orient the spacecraft in a direction which maintained the maximum amount of maneuvering control during the final stages of spacecraft reentry.

Attitude determination and control is an increasingly important component of spacecraft operation. As requirements for satellite orbit determination and sensor data interpretation become more stringent, the knowledge and controllability of spacecraft attitude will become increasingly more important. Improved technologies and spacecraft computers, digital sensors, and solid-state arrays are expected to lead to significant improvements in attitude sensing and attitude determination accuracies over the next several years.

CHAPTER FIVE

SATELLITE TRACKING AND POSITIONING

Satellite tracking and positioning refers to the process of measuring observable quantities from which the position of a satellite in space can be deduced, and using these measurements to determine the satellite's position at current and future times. Satellite positioning is also referred to as satellite orbit determination.

Many techniques have been used to measure the position of a satellite in space. These measurements have been accomplished by radar systems, cameras, and other devices on the ground, which are discussed in this chapter. In addition, newer techniques based on instrumentation carried on board satellites to supply data for tracking and positioning are now being developed. These are also discussed here.

Historically, the first technique for satellite tracking was that of ground station tracking. Ground stations were installed around the world from the beginning of the space program in order to provide observations of satellite positions in space from a number of locations. Observational data are processed in order to determine an orbit which is a best fit to the data. Generally, the orbit determination process involves either a least squares or a recursive Kalman filtering technique for estimating the satellite orbit from the observed data. The data can take the form of either distance or angular measurements, or a combination of the two.

More recently, some satellites have carried radar altimeters which measure the vertical distance between the satellite and the surface of the earth. Altimeters have a number of

applications to geodetic and oceanographic disciplines. However, the altimeter measurement is a useful observation for orbit determination purposes, as well. A number of applications of satellite radar altimeters are included in this chapter.

A final technique, satellite-to-satellite tracking, is just now being brought into operation. Satellite-to-satellite tracking is based on the general idea of having one satellite track another. As is discussed in the following sections, satellite-to-satellite tracking offers a number of possibilities for improving the orbit determination process and in furthering investigations of the global geoid.

4.5.1 Ground Tracking Systems

Introduction - Ground tracking systems have been installed in many locations around the world in order to observe satellites in space. Data collected from ground tracking systems have been the primary source of information for determining the orbits of satellites, for predicting their positions, and for developing global gravity models. These data are also used for precise determination of the positions of the tracking stations. A wide variety of technologies have been drawn upon in developing ground stations and many different types of tracking equipment are used. This section discusses the fundamentals of ground tracking systems and gives several examples to illustrate these fundamental concepts.

Ground tracking systems are used to collect data for many different purposes. Often, tracking systems are included as part of a complete ground station whose purposes are not only to track satellites, but also to collect telemetry data and to transmit command data to satellites. Ground stations are also employed as part of range safety systems whose primary

purpose is to determine whether or not a launch is successful and to avoid accidents resulting from launch vehicles that go off course. Furthermore, ground stations support not only earth orbiting satellites, but also deep-space missions such as Mariner, Pioneer, Viking, and many others.

Ground tracking systems are classified into two general categories, active and passive. Active ground stations transmit signals (usually radio) to satellites. These signals are either retransmitted or reflected back to the ground station for further processing. Passive ground stations do not transmit. They receive signals transmitted by active satellites. Both types of ground tracking systems are widely employed for the applications previously described.

Ground tracking systems have many operational limitations. Some of these are imposed by weather or time of day conditions. Certain systems discussed in the following section can be operated only in fair weather, night time, or other special time periods (twilight, for example). Although some monitoring stations have been operated on board specially designed tracking ships in order to provide coverage in ocean areas, most ground stations are limited to land-based operation. Furthermore, most tracking stations have been developed for operation of a fixed location. However, some of the new stations are specifically designed for mobile operation in order to collect data from a number of different sites.

The types of data that are collected at ground stations include the following:

- Range - Radars and lasers can measure the distance from a ground station to a satellite. This is done by transmitting a signal from the ground station to the satellite, receiving the signal returned

from the satellite, and measuring the round trip return time.

- Range Rate - Measurements of the rate of change of the radial distance, or range rate, can be made by observing the Doppler shift in a transmitted signal. These measurements can be performed by both active and passive ground tracking systems.

- Angle Measurements - Observations of the angular position of a satellite with respect to a given coordinate system at the ground station can be made in a number of ways. Angles can be measured photographically by observing the satellite relative to stars at known orientations. Another technique involves the use of radar servo control systems which position a tracking radar at the orientation of maximum signal strength. This positioning provides angular measurements as well as the range and range rate data. Angles are also determined by interferometry (Section 1.2.7, Unit One).

- Time - In order to interpret data collected by ground tracking systems, it is necessary to have precise time measurements associated with the observations. For this reason, ground tracking systems employ highly accurate clocks in their operational configurations.

The general concept of a ground tracking system is illustrated in Fig. 4.5-1, which shows a transmitter sending a signal from the ground station to the satellite (for active systems), or from an onboard transmitter to the ground station (passive systems). In active systems, the satellite reflects or retransmits the signal to the receiver at the ground station.

The times associated with the transmitted and received signals are available from the time standard and timing unit included in the ground station equipment (for some systems the timing unit is contained in the satellite). A recorder, usually

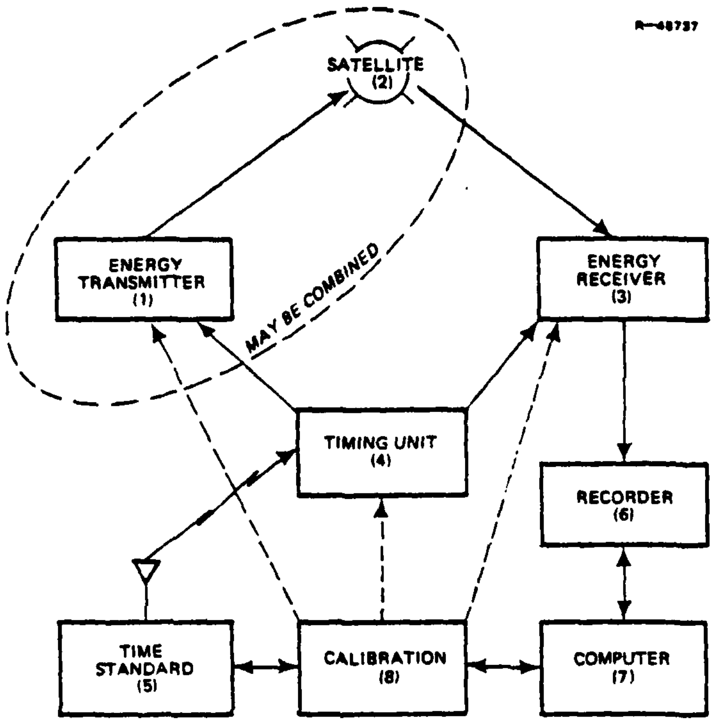


Figure 4.5-1   Ground Tracking System Conceptual Diagram

involving magnetic tape combined with a computer, makes a record of the observed data collected at the ground station.

Since the accuracy of the ground tracking systems is very important, a significant effort is devoted to calibration. Calibration systems employ a variety of external references in order to measure the performance of a ground tracking system and to allow station personnel to provide a level of maintenance that assures the continued accuracy of the system.

Selected Ground Tracking Systems - In order to illustrate the foregoing concepts, a few examples of ground tracking systems are described. To provide a discussion of all systems that have been employed to track satellites would be beyond the scope of these lecture notes. Instead, a few examples have been selected to illustrate the ideas described earlier and to include those systems that have been significant in ground tracking operations in recent years.

C-Band Radars - C-band radars are active tracking devices that transmit signals in the frequency range of 5.4 to 5.9 GHz to the satellites or missiles being tracked. These radars can provide skin tracking data by observing the signals reflected from the object being tracked. The radars can also operate using satellite beacon transponders which receive transmitted signals from the ground radars and retransmit (on a slightly different frequency to avoid interference) the signal back to the ground station. C-band radars have been operated by NASA and the Eastern Test Range (ETR) for a number of applications including precision orbit determination and range safety. Generally, the C-band radars are limited to earth-orbit applications since they do not have sufficient range to track deep space missions.

C-band radars provide range measurement accuracies of 1 to 10 m, range rate accuracies of 0.5 to 3.0 cm/sec, and angular accuracies of approximately 5 min. The C-band radars have been an integral part of the space program for the past twenty years and are expected to continue to be important in the future.

Doppler Tracking - Doppler systems are examples of passive ground tracking systems. These are closely related to the applications of the Navy Navigation Satellite System dis-

cussed in Chapter Six. Satellites tracked by Doppler stations employ beacons which transmit signals at pairs of frequencies to reduce the errors due to ionospheric refraction. The most common frequency pairs are 150 MHz/400 MHz and 162 MHz/324 MHz. Ground tracking stations can measure the Doppler frequency shift in the signals received from the satellites. These measurements of Doppler frequency shift are used to compute the range rate of the satellite with respect to the ground stations. Generally, such range rate measurements can be made to an accuracy of one cm/sec. These data are employed in the development of highly accurate satellite orbits.

Laser Systems - Laser tracking systems are examples of active distance measuring or ranging systems. Such systems are discussed in Unit One in connection with lunar laser ranging. They are also employed to track earth orbiting satellites. Laser stations for tracking earth satellites are operated by NASA, the Smithsonian Astrophysical Observatory, and the Air Force Geophysics Laboratory (formerly called the Air Force Cambridge Research Laboratory). As is the case for the lunar laser ranging systems, satellites to be tracked by lasers are equipped with corner cubes specifically designed to provide a highly reflective surface for returning the transmitted laser signal to the ground station.

Laser systems provide only measurements of range,* but the accuracy of these ranging systems is very good. Laser ranging systems have generally demonstrated an accuracy between 5 cm and 1 m. Further improvements in laser systems are likely to lead to ranging accuracies between 1 cm and 3 cm over the next few years.

*Angular observations may be derived from the antenna control system.

Laser ranging systems are limited to operation in clear weather only. Atmospheric attenuation during periods of cloudiness or rain can severely limit their effectiveness.

Optical Tracking Systems - Another form of passive ground tracking system that has been employed since the early days of satellite tracking is based on a specially designed camera of large focal length. Such systems have been discussed in Section 1.4.2 (Unit One), to which the reader is referred for further information.

Unified S-Band Tracking Systems - The Unified S-band system, developed by NASA, is another example of an active tracking system. This system, operating at frequencies between 2.2 GHz and 2.3 GHz, provides measurements of range, range rate, and angular position. The system was developed originally for the Apollo project, but has provided a significant amount of ground tracking data for both earth orbiting and deep space missions.

The system is called *unified* because the signal tracked by the ground system contains not only a component for measuring the range and Doppler shift, but also components for transmitting and receiving the command and telemetry data for the space vehicle. Satellites designed to be tracked by the Unified S-Band system carry *transponders* which receive the signal transmitted from the ground station, change the frequency in a precisely controlled way, and retransmit the signal to the ground station. The transponder also decodes command data and transmits telemetry data. System accuracies are between 5 and 10 m in range, about 0.2 mm/sec in range rate, and between 5 and 10 $\widehat{\text{min}}$ in the determination of angles.

Summary - In order to combine the advantages of a number of tracking systems, many satellites carry equipment to operate with more than one tracking system. For example, SEASAT carried Doppler beacons, an S-band transponder, and laser corner cubes. This permitted data collection at a number of ground stations in different locations. Coverage from a variety of regions was very important in developing orbits of the required accuracy for SEASAT operations.

Future tracking operations will be supplemented by satellite-to-satellite tracking, discussed in Section 4.5.3. Satellite-to-satellite tracking will reduce many of the operational limitations of ground-based satellite tracking, but some ground stations will still be required in order to support special requirements such as range safety, high accuracy (laser ranging for example), and others. Thus, ground tracking systems will continue to be an important aspect of satellite tracking for many years.

4.5.2 Satellite Altimetry

A satellite radar altimeter is an onboard radar that measures the vertical distance between the satellite and the earth's surface directly below it. This measurement is made by finding the time required for the radar signal to travel from the satellite to the surface and back. To date, satellite radar altimeters have been microwave devices (the radar signals are transmitted at a frequency of 13.9 GHZ), but, in principle, other types of radars (lasers, for example) could also be used for some missions. Satellite radar altimeters have been carried aboard SKYLAB, the Geodynamics Experimental Observation Satellite (GEOS-3), and SEASAT-1.

Applications of satellite radar altimeter data are numerous. These include estimation of the geoid, deflections of the vertical, and gravity anomalies in ocean areas; mapping of ocean currents, tides, and waves; detection of significant bathymetric features; and terrain mapping in land regions. The nature of the satellite radar altimeter measurement process and various applications are discussed in following sections. Examples are drawn from the GEOS-3 and SEASAT-1 missions.

Fundamental Concept - A satellite radar altimeter measures the height of the satellite above the surface of the earth directly beneath it. Ground tracking stations determine the height of the satellite above the reference ellipsoid. Correction of the measurement for altimeter biases and ocean tides yields the undulation of the geoid. This is illustrated in Fig. 4.5-2. The mathematical equations relating the undulation of the geoid to the deflection of the vertical and the gravity anomaly may be used to determine the gravity field in ocean regions from altimeter data. The radar transmits a pulse of energy with a relatively narrow time width (3 ns in the case of SEASAT). This non-zero pulse width causes a spreading of the energy on the surface, producing an averaged altitude measurement over a circular spot of radius:

$$\rho = \sqrt{2hc\tau} \qquad (4.5\text{-}1)$$

where h is the altitude of the satellite, c is the speed of light, and τ is the width of the pulse. This is illustrated in Fig. 4.5-3.

The height above the ellipsoid (sea surface height, SSH) measured by this process is due both to geoid undulations and to dynamic oceanographic effects.

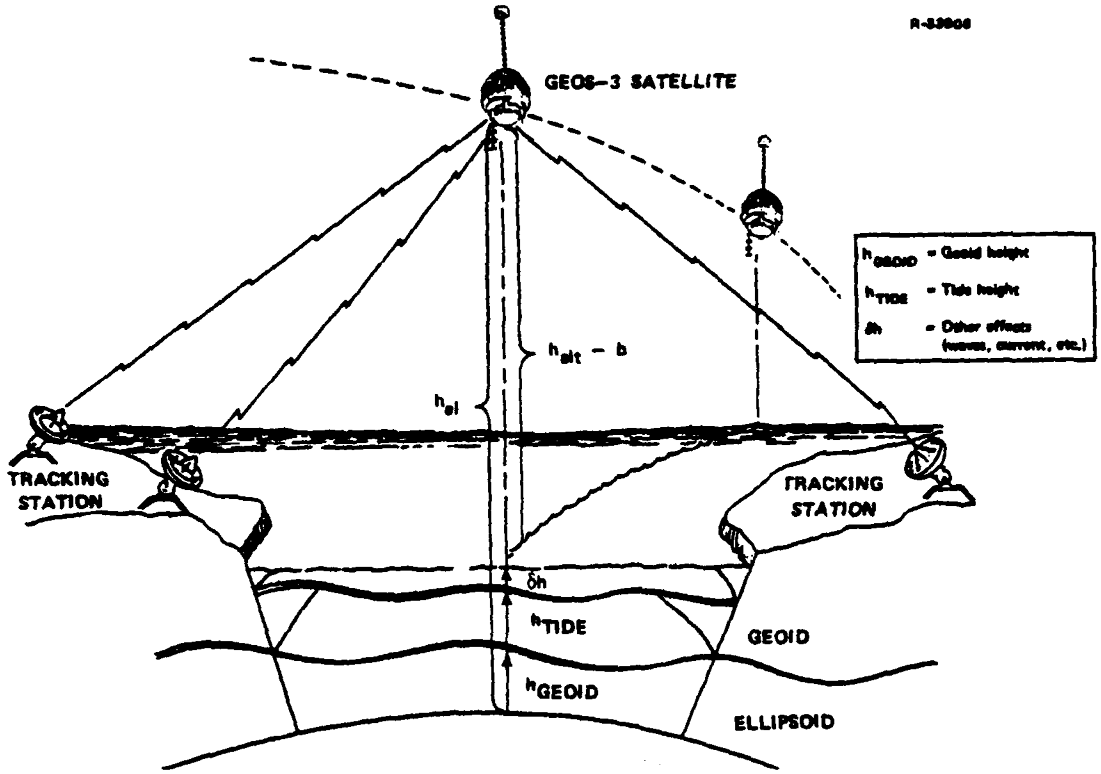


Figure 4.5-2   Satellite Radar Altimeter Measurements

$$\text{SSH} = \text{Geoid height } (h_{geoid}) + \text{tide height } (h_{tide}) + \text{sea state (waves), currents, and other small effects } (\delta h) \quad (4.5\text{-}2)$$

Oceanographic effects are generally small compared to the size of the geoid undulations and, for many applications, have been neglected. However, the accuracy of the SEASAT-1 orbit determination process and the altimeter instrument have led to a number of oceanographic investigations in which maps of ocean currents are developed. This is discussed further in later sections.

A fundamental problem of satellite radar altimetry is the separation of geoidal and oceanographic variations. Because these terms are additive, it is not possible to separate them

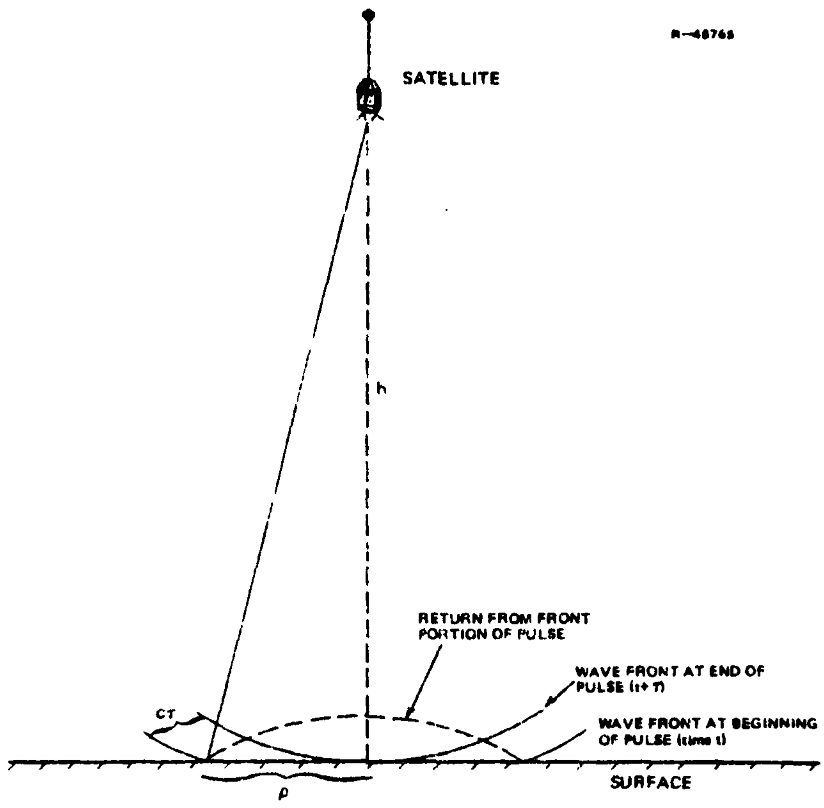


Figure 4.5-3   Altimeter Measurement Geometry

exactly. Attempts to do this have been based on assumptions concerning relative sizes and spatial scales, and on the use of data supplied by other sources. This is discussed further in the following section.

Measurement Errors - The measurement of the height of the dynamic sea surface is affected by a number of error sources. Some of these effects can be partially corrected, while others are irreducible. Principal error sources include the following:

- Radar Altimeter Instrument Errors - The instrument errors consist of random noise resulting from variations in the altimeter electronics and bias errors resulting from equipment delays in transmitting and receiving the signal. The random effects can be reduced only by averaging the data or by taking more tracks over a given region. The bias can be calibrated accurately by ground tracking.

- Antenna Pointing Errors - Attitude control errors in the satellite mean that the antenna is not necessarily aligned along the local vertical. Attitude control is generally accurate to within a degree, but variations in the antenna radiation pattern can cause loss of signal strength if the antenna is not exactly vertically aligned.

- Atmospheric Refraction - The refraction effect on a signal transmitted from the satellite to the ground would cause an error in estimating the height of approximately 2.5 m. However, using average values for atmospheric temperature, pressure, and humidity, it is possible to correct for the height measurement error caused by refraction to an accuracy of 5 to 8 cm. To perform a more precise correction will require measurements of local temperature, pressure, and humidity. Such corrections are being applied in the analysis of the SEASAT data.

- Radial Orbit Determination Uncertainty -An error in the determination of the height of the satellite above the reference ellipsoid translates directly into an error in the determined geoid height. The current state of the art in orbit determination is such that the radial distance can be determined to an accuracy of approximately 1 meter. Experimental work is now in process to reduce the radial orbit determination error for SEASAT-1 to below 50 cm.

- Dynamic Oceanography - For geodetic applications, the oceanographic effects cause

an uncertainty in the estimated geoid height. Oceanographic effects do not generally exceed 30 to 40 cm except in regions of large ocean current systems and near coastlines.

Satellite Altimeter Data Coverage and Data Examples - Satellite altimeter data are collected along the surface subtracks of the satellite orbits. For GEOS-3 the inclination of the satellite orbit with respect to the equator was 115 deg. For SEASAT-1 the inclination of the orbit was 108 deg. Examples of the orbit coverage in different areas for both GEOS-3 and SEASAT are shown in Figs. 4.5-4 and 4.5-5. These figures illustrate the variations in coverage density in different parts of the ocean.

The estimation of geoid height is generally accomplished by smoothing the measurements of the geoid along the tracks of the satellite and applying various contouring, gridding, and statistical techniques to calculate the ocean geoid height over regions of various sizes. For example, the Defense Mapping Agency has calculated one-degree mean geoid heights from the GEOS-3 data.

Estimates of the deflection of the vertical are required for accurate inertial navigation of terrestrial vehicles (like submarines). The deflection of the vertical in a given direction is the negative of the partial derivative of the geoid height in that direction (discussed in Chapter Three of Unit One). Accordingly, the estimation of deflections of the vertical from satellite radar altimeter data requires a differentiation of the data. This is generally done by applying a differentiating filter to the data after initial smoothing. As with the geoid heights, mean deflections of the vertical can be produced by various regularizing or statistical techniques. The accuracy of deflections of the vertical produced from the

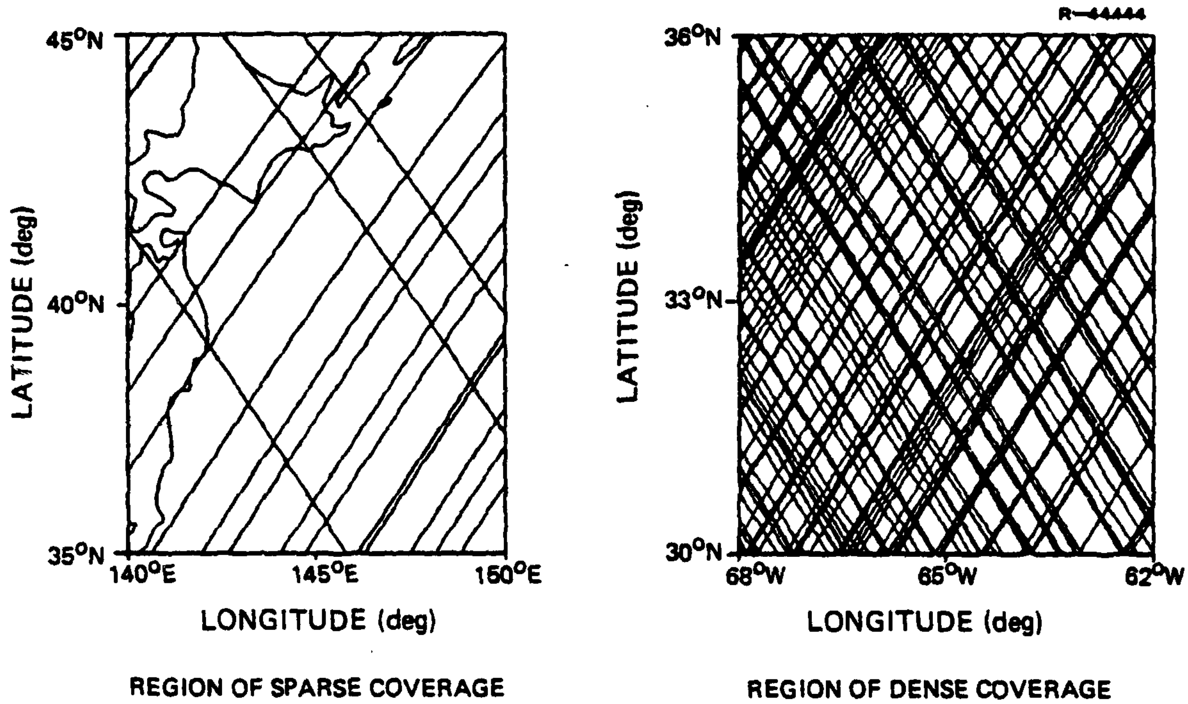


Figure 4.5-4 Examples of GEOS-3 Coverage

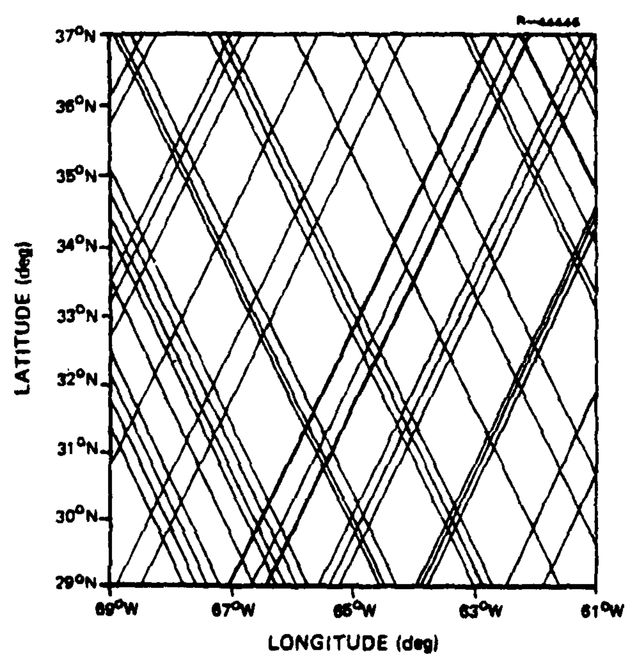


Figure 4.5-5 Representative SEASAT-1 Coverage Pattern

GEOS-3 satellite altimetry data has been estimated as two $\widehat{sec}$ (RMS). However, in some regions the accuracy could be substantially worse because the altimeter is not able to resolve the fine structure of the local geoid variations. Examples of GEOS-3 data and estimation of geoid undulations and deflections of the vertical are shown in Figs. 4.5-6 and 4.5-7. The SEASAT-1 data would have been accurate to approximately one $\widehat{sec}$ (RMS), but the premature failure of the spacecraft meant that the full data set was not collected. Thus, the estimation accuracy was significantly degraded.

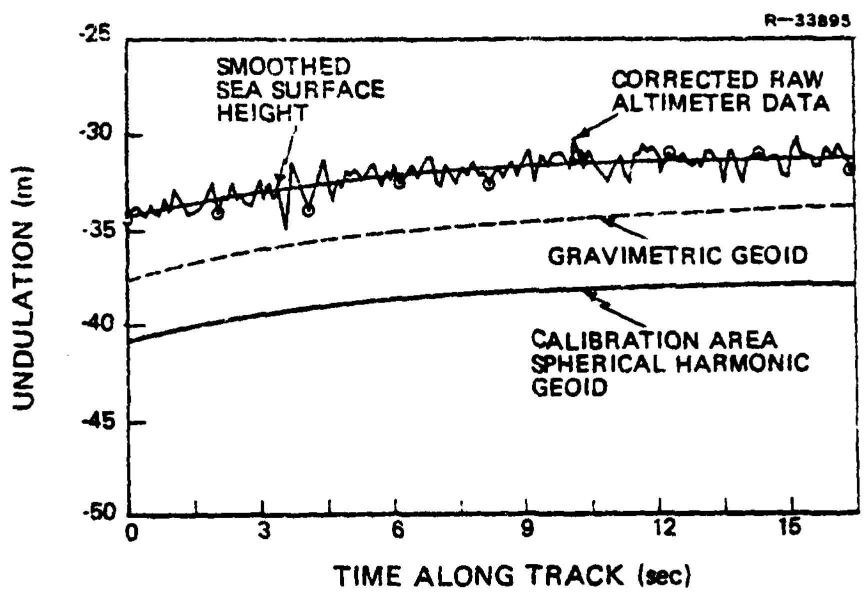


Figure 4.5-6 Comparisons of Estimated Geoid Undulation

Estimation of mean gravity anomalies from satellite radar altimeter data may be carried out by statistical techniques that use the correlations between gravity anomaly variations and geoid height variations. Mean gravity anomalies of one-degree resolution have been calculated to an estimated accuracy of approximately six mgal (RMS).

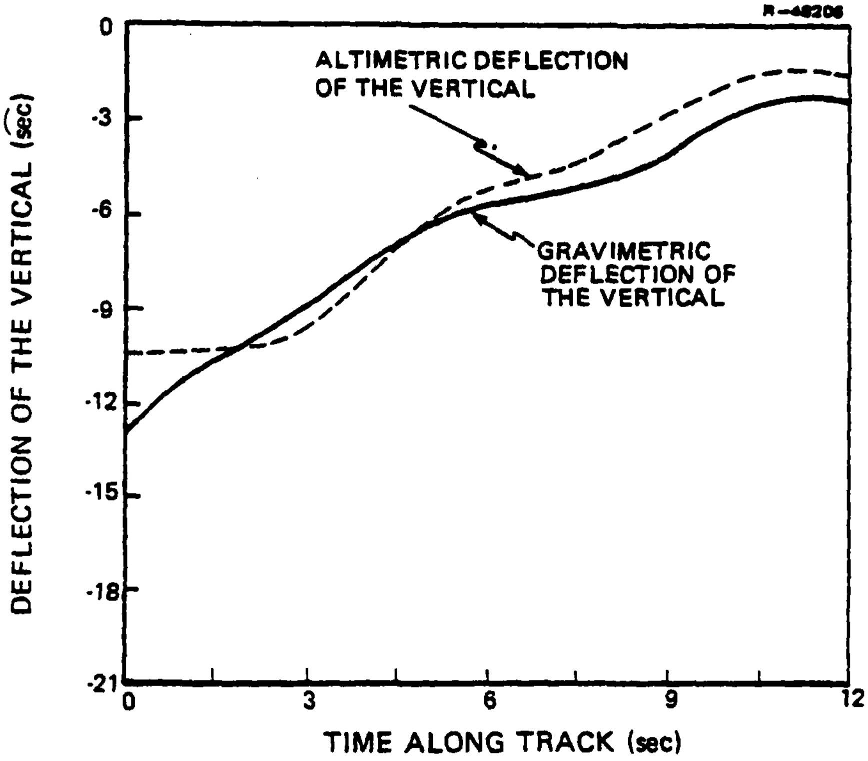


Figure 4.5-7 Comparison of Estimated Deflections of the Vertical

Oceanographic Applications of Satellite Altimetry - Since dynamic sea surface effects can be measured directly by satellite radar altimeters, many researchers have directed their attention towards determining oceanographic phenomena from satellite altimeter data. As discussed earlier, a precise separation of geoid variations from oceanographic variations is not possible, but generally the geoid variations are on a larger scale than the oceanographic variations. This can aid in distinguishing the two effects. Furthermore, in some regions, results from accurate gravity surveys are available which can be used to estimate local gravity and geoid variations. This can also help to separate geoid height variations from oceanographic variations.

Certain types of ocean currents, known as geostrophic currents, cause changes in the local sea surface height which can be measured by satellite radar altimeters. There is an approximate relationship between the velocity of the current (V) and the change in oceanographic height (Δh) sensed by the satellite, which can be used to estimate the velocity of the current from the altimeter data. This equation is given by

$$V = \frac{g\Delta h}{2\omega \sin \phi \sin \alpha \, \Delta L} \qquad (4.5\text{-}3)$$

In this equation, ω is the earth's rotation rate, ϕ is the geodetic latitude, α is the angle between the current flow and the satellite subtrack, ΔL is the width of the current as measured along the satellite subtrack, and g is the acceleration of gravity.

Experiments have been performed using GEOS-3 data to estimate the velocity and boundary locations of the Gulf Stream, one of the more prominent ocean currents. The results of these experiments show that the velocity of the current can be estimated to an accuracy of approximately 30 cm/sec. The boundaries of the current can be located to within approximately 40 km.

Since other techniques of using satellite data to map ocean currents rely on infrared sensing of temperature differences, it is significant to note that satellite altimeter data can be used to sense either cold-water currents or currents at the same temperature as the surrounding ocean. The accuracy of the altimeter data in this oceanographic application is comparable with the best infrared surveys. Future satellite radar altimeters should be able to perform with substantially more accuracy in this application.

Another oceanographic application of satellite radar altimeter data is the estimation of significant wave height.

Significant wave height is usually expressed in terms of a parameter, $H_{1/3}$, which is the average height of the highest one-third of the waves above mean sea level. The concept of significant wave height estimation is based on the fact that the pulse of energy transmitted by the satellite radar altimeter and reflected back from the ocean's surface is spread out by any roughness in the local sea surface. If the sea surface were a perfectly smooth reflector, then the reflected pulse would be nearly a step function. Since the sea surface is not perfectly smooth, the return pulse is spread out in time over 10 to 15 ns. The amount of this spreading is determined by the roughness of the sea surface. By analyzing the slope of the return signal, it is possible to infer the average roughness of the sea surface and to relate that to the height of the waves. This is illustrated in Fig. 4.5-8, which shows the change in slope of the return signal power as a function of significant wave height.

Bathymetric Mapping - For marine geological applications and submarine navigation, it is important to know the location of seamounts. A seamount is an underwater mountain of volcanic origin. Seamounts can rise several kilometers above the surrounding ocean floor. While isolated seamounts as well as seamount chains are plotted on bathymetric charts, it is believed that many additional (as yet uncharted) seamounts exist in various ocean areas.

Because of the mass density contrast between the seamounts and the surrounding ocean water, there is a change in the local gravity which, in turn, affects the local geoid height. This change in geoid height can be measured by a satellite radar altimeter. Thus, it is possible to make direct inferences about underwater geological structures from satellite data. The ability of the SEASAT radar altimeter data to detect seamounts is illustrated below. In Figs. 4.5-9 and 4.5-10 are

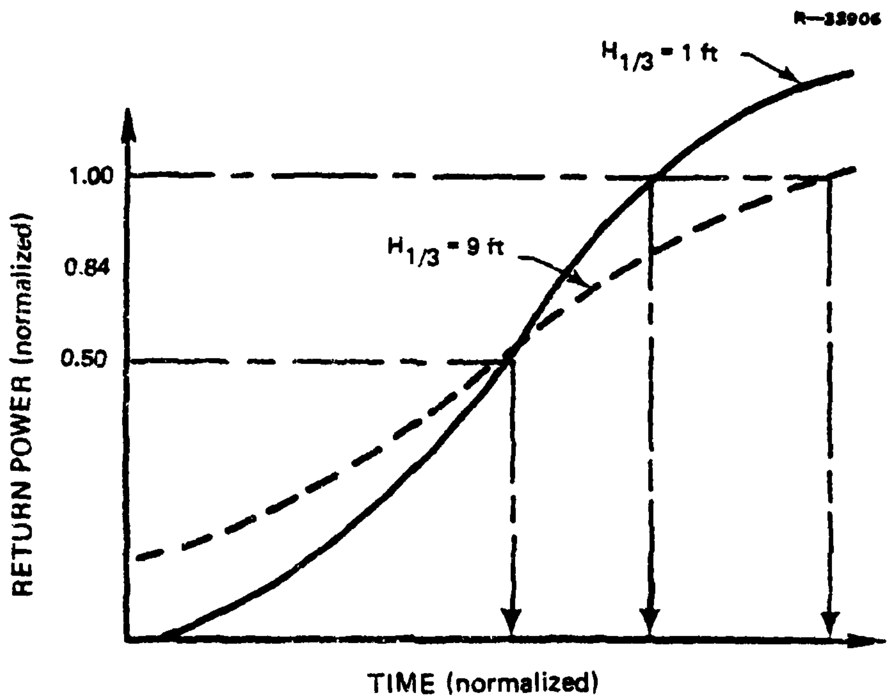


Figure 4.5-8 Effect of Sea State on Satellite Radar Altimeter Return Signal

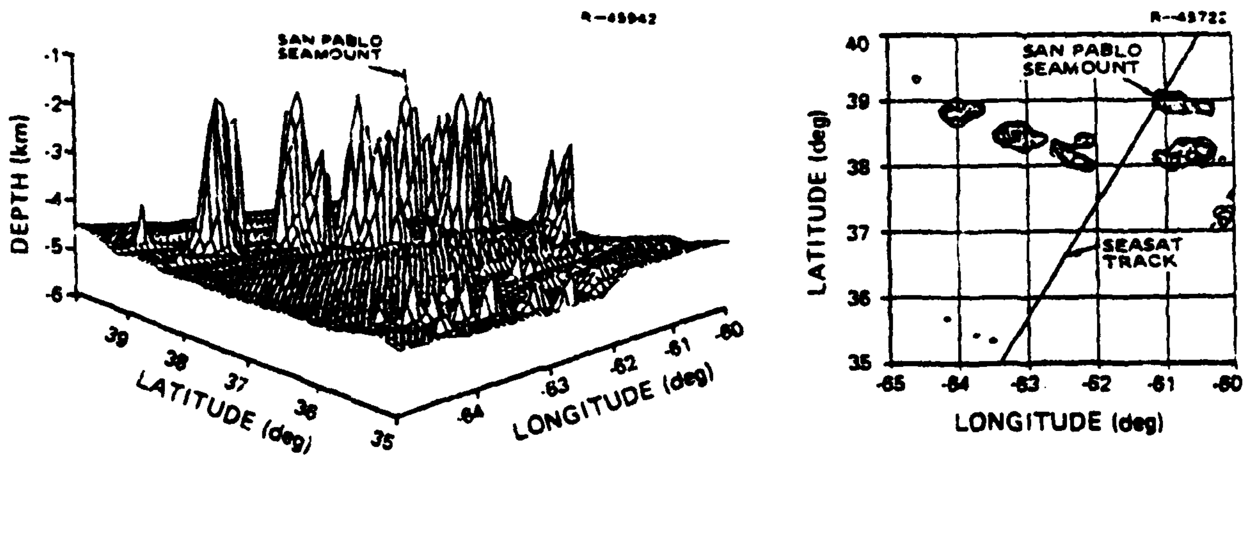


Figure 4.5-9 New England Seamounts and SEASAT Subtrack

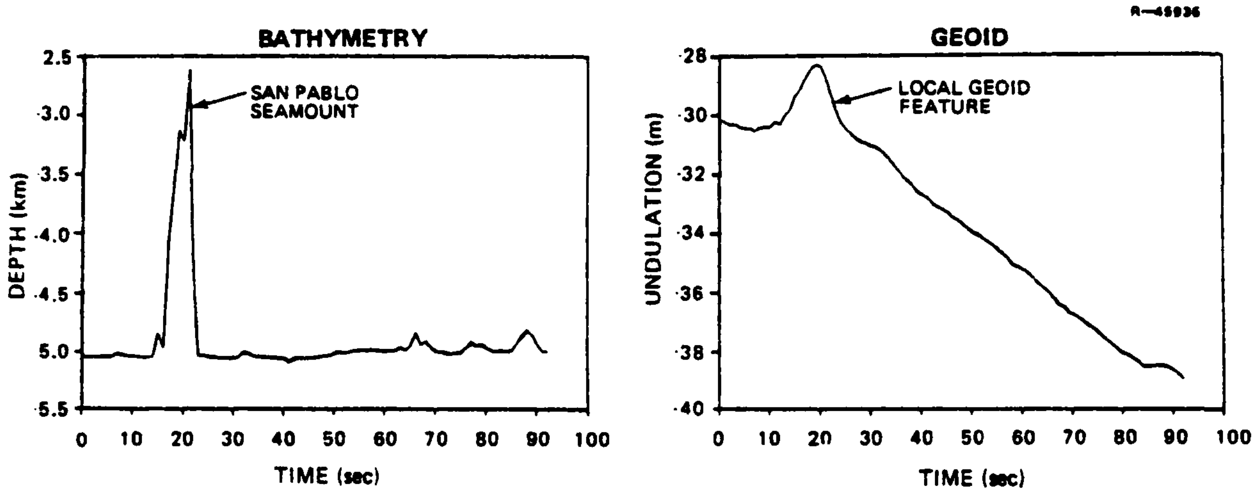


Figure 4.5-10 Bathymetry and Sea Surface Height Along SEASAT Track

displays of the bathymetry in the New England seamount region compared with the bathymetry and geoid height along a track of SEASAT data through the region. Note that the rise in geoid height coincides exactly with the rise in the bathymetric structure. By observing similar patterns in the local geoid height data it is possible to determine the location of seamounts that are sufficiently close to the surface and of sufficient size to produce a measurable change in the local geoid.

<u>Terrain Mapping</u> - Although satellite radar altimeters are designed primarily to operate over ocean regions, results from the GEOS-3 program have shown that these altimeters are capable of mapping land features in certain circumstances. Although the analysis is still in an experimental stage, the results obtained from the overland data are very encouraging. An illustration of the ability of the GEOS-3 radar altimeter to track overland regions is shown in Fig. 4.5-11.* For the

*The curve marked AGC is the altimeter automatic gain control voltage, a measure of the reflected signal power.

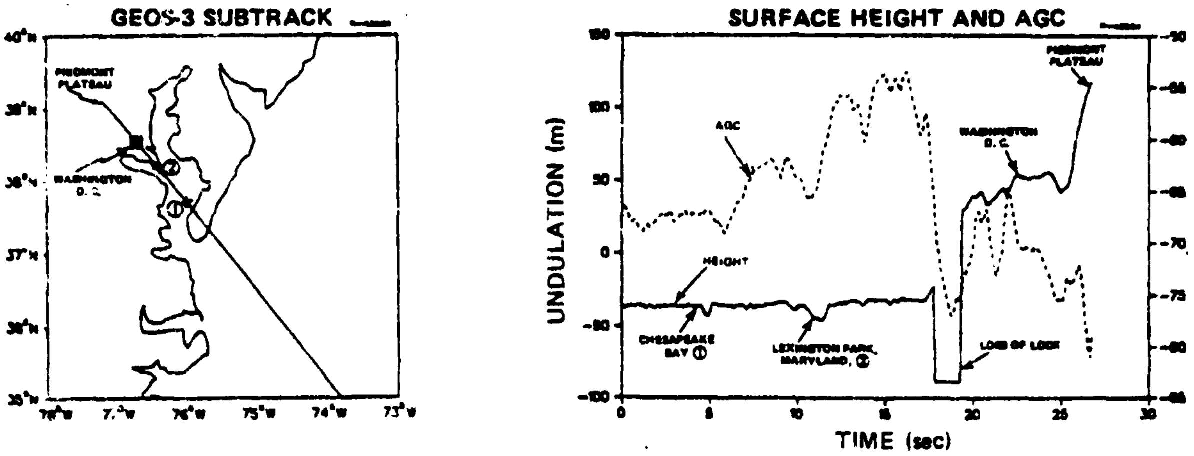


Figure 4.5-11 Example of GEOS-3 Overland Data

track shown, the satellite was moving to the northwest from the Atlantic Ocean, over the Chesapeake Bay, through Washington, D.C., and continuing northward over the Great Lakes. For most of the overland portion of the track, the radar altimeter produced accurate terrain profile data, although there are periodic intervals of invalid data where the terrain variations are too rapid for the radar to measure.

Other applications of overland radar altimeter data under investigation include detection of changes in local elevation caused by geophysical phenomena such as earthquakes and extractions of petroleum or water, as well as the estimation of soil moisture by analyzing the detailed structure of the energy that is reflected back from the ground to the altimeter.

Future Satellite Radar Altimeter Programs - With the premature termination of the SEASAT mission and the end of the GEOS-3 mission, there are (in 1980) no satellite radar altimeters in operation. The next spacecraft being planned by NASA

to include satellite radar altimeters are the National Oceanic Satellite System (NOSS) satellites, which will be similar to SEASAT (but more advanced), and an ice-mapping mission which will use the altimeter to detect ice and to monitor changes in ice levels over a period of time. Both of these missions are being planned for launch in the mid-1980s and are expected to provide significant advances in geodetic, oceanographic, and climatological applications of satellite radar altimetry.

4.5.3 Satellite-to-Satellite Tracking

Background and Fundamental Concepts - As the name suggests, satellite-to-satellite tracking involves the measurement of the relative range and/or range rate between two satellites. Satellite-to-satellite tracking is a relatively new concept as compared to ground-based satellite tracking, and it is still in the experimental stage. The technique is expected to become operational in the 1980s, but the programs accomplished to date have been strictly for research and development. There are a number of potential applications of satellite-to-satellite tracking. Among the most important are the following:

- Satellite Orbit Determination - The data that are collected from satellite-to-satellite tracking systems may be used to determine the orbit of a satellite. This orbit determination may be performed either on board a user spacecraft, or at ground stations.

- Data Communications - A knowledge of the orbit of a user satellite determined from satellite-to-satellite tracking data can allow the pointing of a data communications antenna in the proper direction for high-rate digital communications.

- <u>Gravity Field Determination</u> - Precise measurements of the range and/or range rate between two satellites in combination with ground tracking data can provide a basis for the determination of part of the fine structure of the earth's gravity field. This fine structure causes anomalous accelerations in the satellite's orbit which can be measured to infer local gravity structures.

The initial motivation for satellite-to-satellite tracking came out of the need for orbit determination during the Apollo project. Global ground tracking coverage for the Apollo spacecraft was difficult for a number of reasons. First, a ground station can see a low orbiting satellite for only a very small fraction of its orbit. For this reason, it is necessary to have a large number of ground stations to provide global tracking and communications coverage. Second, because of geographical and political factors, a global-coverage network of land-based ground tracking stations is impossible. Thus, during the Apollo project, NASA supplemented its tracking network with ships and aircraft. The difficulty and expense of operating a large number of ground stations motivated the concept of satellite-to-satellite tracking, in which a small number of geosynchronous satellites could provide broad tracking coverage for a wide variety of user satellites. Since the tracked satellites are generally in orbits much lower than geosynchronous altitude, this configuration is known as the <u>high-low</u> approach. The coverage that is available from a single synchronous satellite is illustrated in Fig. 4.5-12. The high-low concept is shown in Fig. 4.5-13.

For the same reasons, support for data communications also motivated satellite-to-satellite tracking. In the 1980s, with the advent of the Tracking and Data Relay Satellite System (TDRSS), NASA will phase out many of its ground stations and

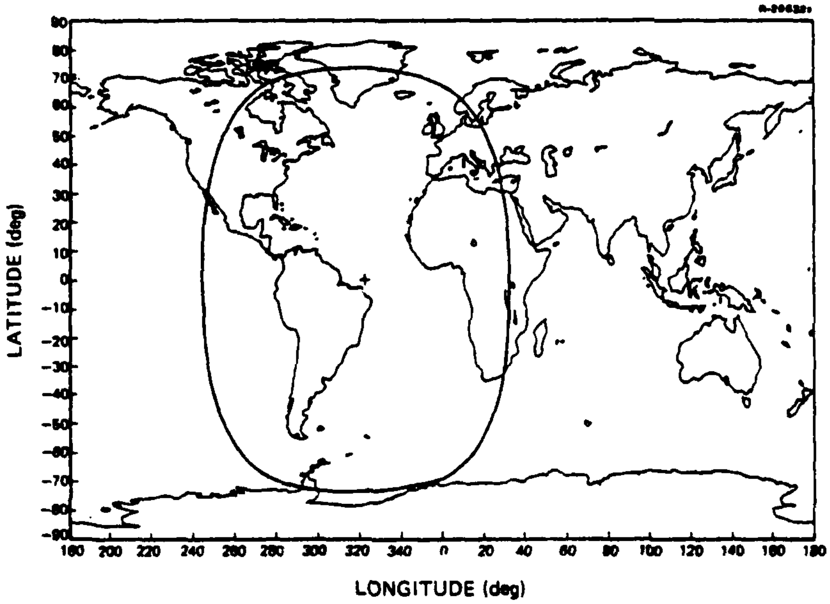


Figure 4.5-12   Geographic Coverage from a Geosynchronous Satellite

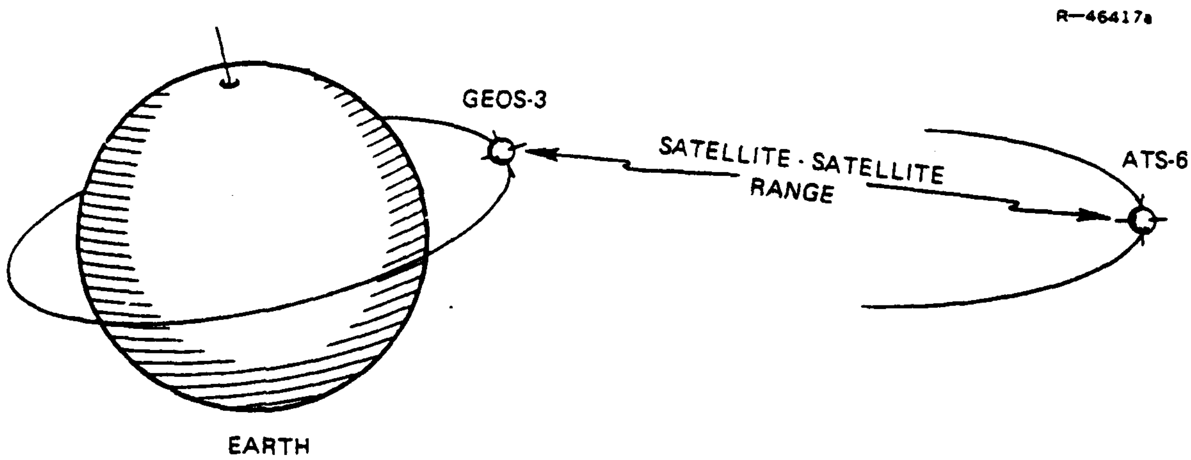


Figure 4.5-13   High-Low Satellite-to-Satellite Tracking Configuration

provide most of its tracking, telemetry, and command services through the TDRSS. For geodetic applications, however, the most important use of satellite-to-satellite tracking is in the determination of the earth's gravity field. This is by far the most difficult application, requiring a much higher degree of accuracy in the measurement of the relative range and/or range rate than is necessary for orbit determination and support of data communications.

There have been satellite-to-satellite tracking experiments involving three major spacecraft systems. All of these have used ATS-6 (as the high satellite) to track lower altitude spacecraft. These were the Apollo-Soyuz spacecraft, the meteorological satellite NIMBUS-5, and GEOS-3. Analysis of the data from these experiments shows that it is possible to provide range rate measurement accuracies of approximately 0.2 mm/sec (RMS) and to use these data to estimate 5 deg mean gravity anomalies.

Another satellite system expected to have a significant application in satellite-to-satellite tracking is the NAVSTAR Global Positioning System (GPS). As currently designed, GPS will not have sufficient accuracy to provide high-resolution geodetic estimates, but will provide highly accurate orbits for a number of user spacecraft.

Fundamental Principles - There are two fundamental approaches to satellite-to-satellite tracking. Both of these approaches will be used operationally in the 1980s for orbit determination and gravity field analysis. These two techniques are referred to as one-way tracking and two-way tracking. One-way tracking involves signal transmission to users who may be passive (i.e., have no transmitter). Thus, the signal communication flows in one direction only. Two-way tracking

involves an active two-way communication path between the satellites (and possibly ground stations). The NAVSTAR GPS is an example of a one-way system. The TDRSS is an example of a two-way system.

One-Way Satellite-to-Satellite Tracking System - The one-way satellite-to-satellite tracking technique is illustrated in Fig. 4.5-14. This technique requires a highly accurate clock on the transmitting satellites so that the user satellite can determine its position, velocity, and time. This determination requires transmissions from four satellites. This is the concept used, for example, in the NAVSTAR GPS, which is discussed in detail in Section 4.7.

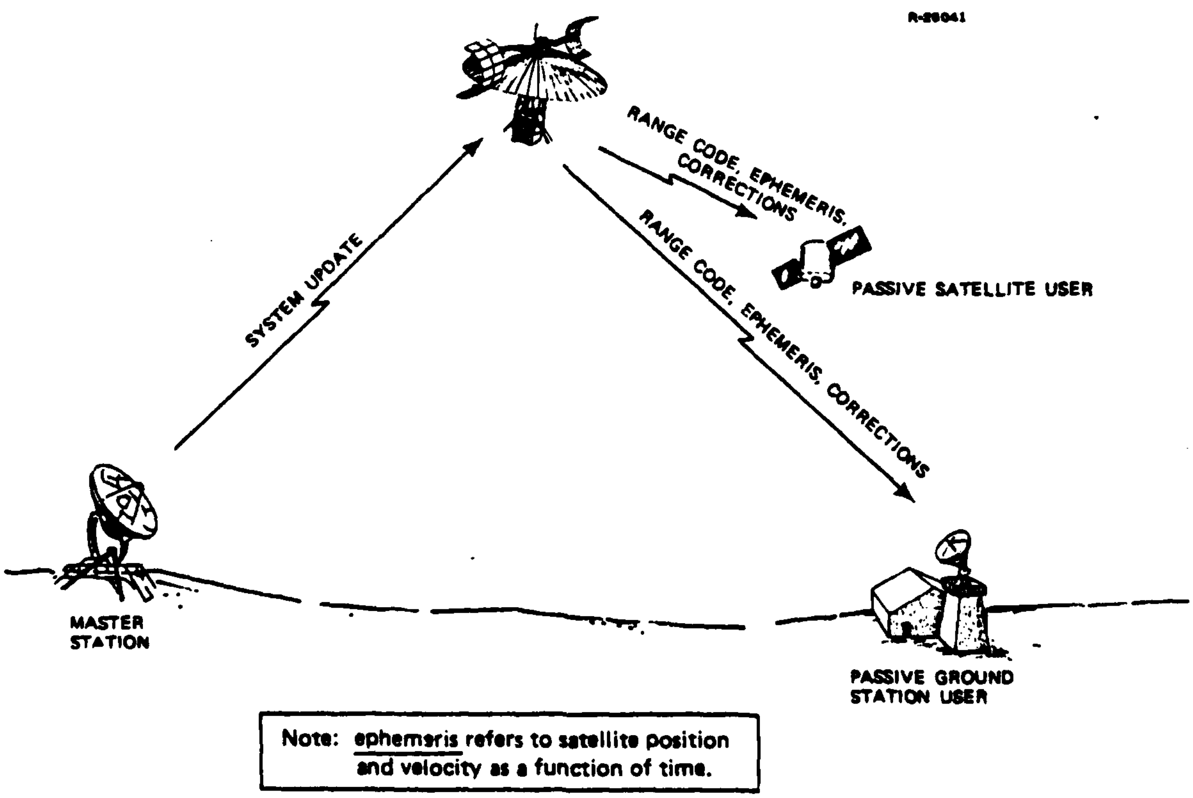


Figure 4.5-14 One-Way System Concept

The advantages of the one-way technique are the following. First, the tracked satellite is not required to transmit. This means that it can determine its own orbital position without the use of onboard transmitting equipment. Second, because the orbit solution can be obtained on board the user spacecraft directly, this solution can be used in a real-time attitude control system as well as for orbit determination. The disadvantages, as compared with a two-way system, are that relatively high accuracy clocks are required. Also, the range rate measurement loses accuracy because of clock frequency drift.

Two-Way Satellite-to-Satellite Tracking - Two-way satellite-to-satellite tracking has been the technique used in experiments with the ATS-6 system mentioned above. Furthermore, since NASA intends to provide data communication services through the TDRSS as its primary function, all satellite-to-satellite tracking offered by NASA in the future will be in the two-way mode. Although TDRSS will be available in the 1980s for data communications and tracking, as currently designed it will not be accurate enough for geodetic applications. NASA is considering new two-way systems specifically for gravity field determination which will be based upon the experience gained from the ATS-6 experiments. The two-way satellite-to-satellite tracking concept is shown in Fig. 4.5-15.

A variation on the high-low concept described earlier is that of the low-low satellite-to-satellite tracking approach. In this method, two satellites would be placed in very similar orbits at a low altitude (150 km). The satellites would track one another continuously and the range rate data would be used to estimate acceleration anomalies in the orbit, and thus, to infer local gravity anomalies. The low-low satellite-to-satellite tracking concept is illustrated in Fig. 4.5-16.

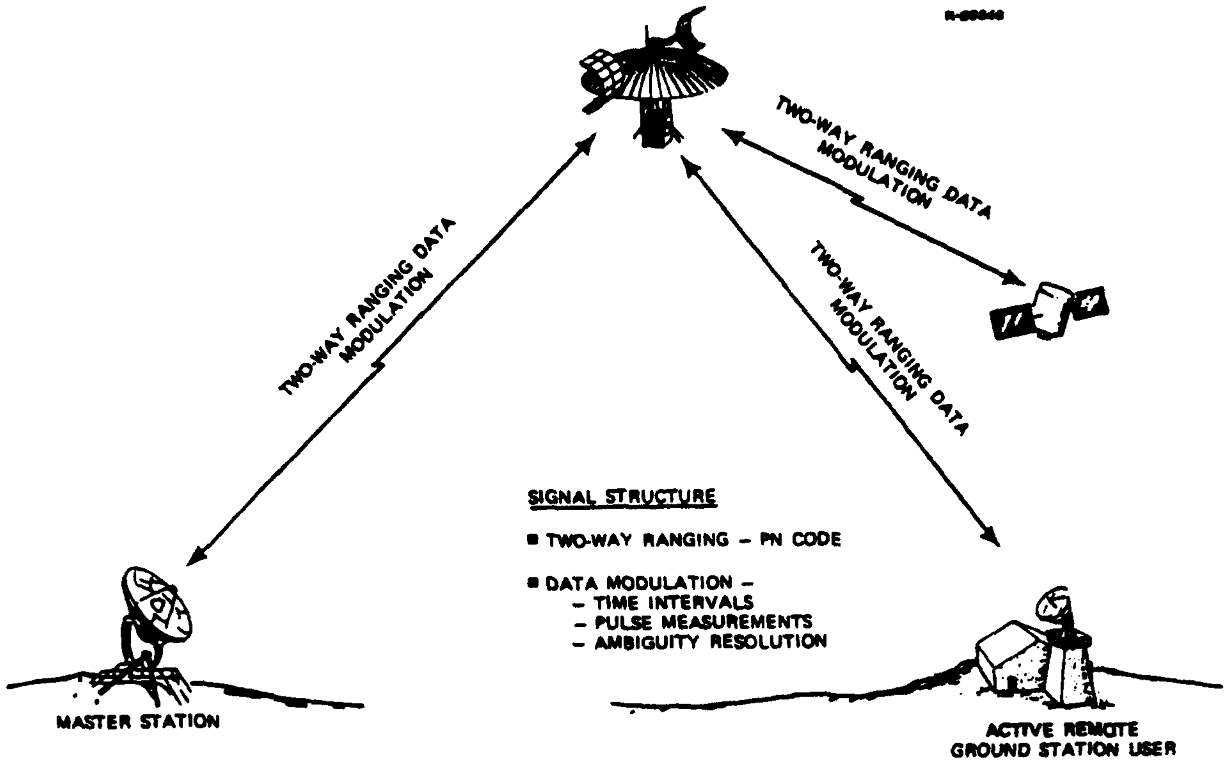


Figure 4.5-15 Two-Way System Concept

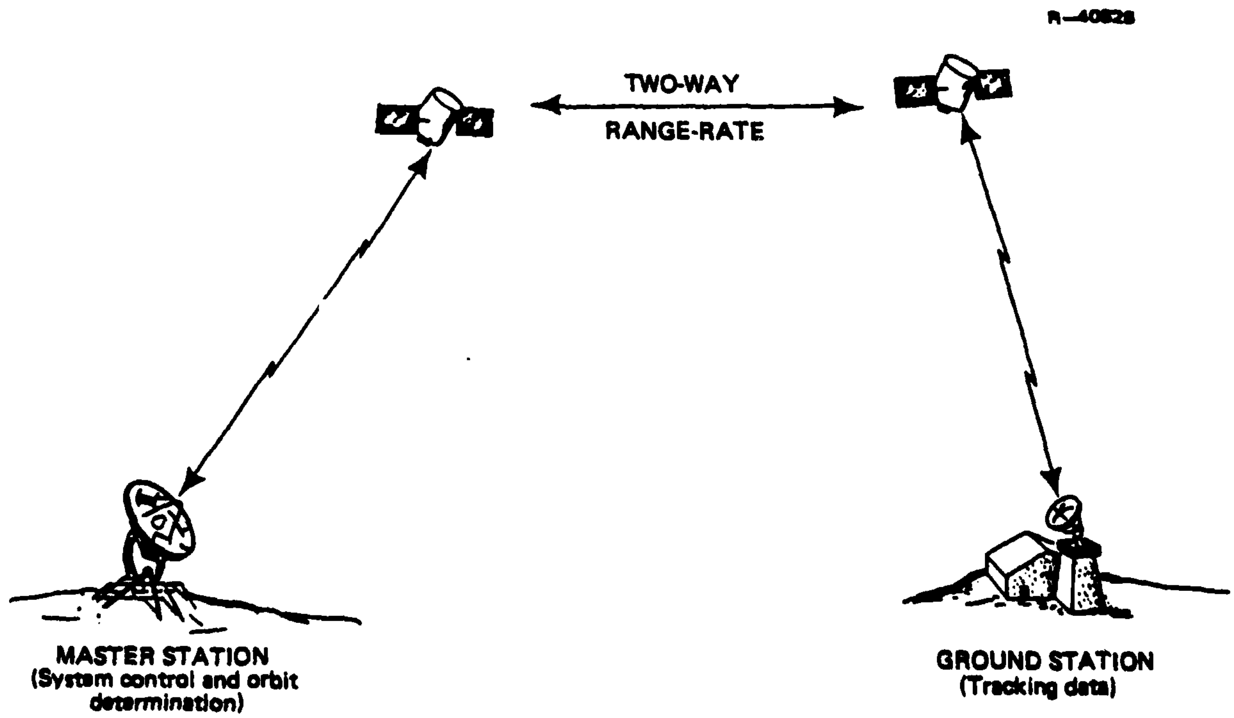


Figure 4.5-16 Low-Low System Concept

In principle, the two-way satellite-to-satellite tracking is more accurate than the one-way method. The primary reason for this is that clock drift and equipment bias errors, cancel out when signal transmissions over the same communications channel occur in both directions.

Orbit Determination Accuracies - This section provides examples of expected orbit determination and gravity anomaly estimation performance from satellite-to-satellite tracking techniques. Satellite-to-satellite orbit determination has been studied using GPS as the high satellite. Three distinct low satellite orbit classes are of interest. These orbit classes include circular orbits (similar to the orbital characteristics for the Navy Navigation Satellite System, discussed in Chapter Six), a high eccentricity orbit, and a low perigee orbit. The orbit characteristics are summarized in Table 4.5-1.

TABLE 4.5-1
USER SATELLITE ORBIT CHARACTERISTICS

SATELLITE TYPE	PERIOD (min)	ALTITUDE (km)	
		PERIGEE	APOGEE
Navy Navigation	105	995	995
High Eccentricity	720	400	40,000
Low Perigee	180	250	8,145

The orbit determination accuracies appear to range between 6 and 35 m (RMS uncertainty) in position. The velocity accuracies range between 0.3 and 5 cm/sec (RMS uncertainty). The periods of high orbit determination accuracy correspond to those periods when the low satellites can receive signals from several GPS

satellites simultaneously, while intervals of lower accuracy correspond to those periods when the low satellite is out of view of GPS.

Results from the ATS-6/GEOS-3 satellite-to-satellite tracking experiment show orbit determination accuracies of approximately 30 m in position and 0.2 cm/sec in velocity. It should be noted that the ATS-6/ GEOS-3 satellite-to-satellite tracking results involve the tracking of the user spacecraft (GEOS-3) by a single high altitude satellite (ATS-6). ATS-6 was tracked separately by ground stations to maintain the accuracy of the estimates of its synchronous orbit. The GPS user satellite orbit determination is accomplished by processing the GPS signals received from four (or more) GPS satellites, which are also in orbits of relatively high altitude.

Gravity Anomaly Determination - The determination of gravity anomalies from satellite-to-satellite tracking data has been based primarily on ATS-6/GEOS-3. The technique for processing this data set is essentially as follows:

- Range Rate Data Smoothing - The satellite-to-satellite tracking data provide a measure of the range rate betweeen ATS-6 and GEOS-3. Since the data are somewhat noisy, it is necessary to smooth them before further processing.

- Differentiation - Differentiating the smoothed range rate data provides an estimate of the acceleration in the line of sight (LOS) direction between the satellites. By defining the mathematical relationships (statistical correlations) between the LOS acceleration anomalies and the gravity structure of the earth, it is possible to infer local gravity anomalies along the satellite subtrack. The collection of a large number of satellite subtracks makes possible a regional or global map of gravity anomalies from satellite-to-satellite tracking data.

Future Satellite-to-Satellite Tracking Programs - As discussed above, GPS and TDRSS will provide considerable satellite-to-satellite tracking data during the 1980s. However, the applications of these systems will be primarily in orbit determination and data communications. To attain more precise results for gravity field determination, it is necessary to establish more accurate systems.

Much research is now devoted to the definition of a potential GRAVSAT mission. There are two principal alternatives for the fundamental mission concept. One involves a high-low geometry similar to that used by the ATS-6/GEOS-3 experiment mentioned earlier. The primary difference for GRAVSAT, however, would be to place a user spacecraft in an orbit that is considerably lower than the 850 km orbit of GEOS-3. In order to attain enough sensitivity to measure the fine structure of the earth's gravity field, it will be necessary to place a low altitude GRAVSAT at an orbital altitude of 150 to 250 km. Accurate range rate measurements (error level of 0.1 mm/sec) should permit the determination of mean gravity anomalies (on a grid of one or two deg) to an accuracy of one mgal. Use of the Space Shuttle is expected to allow user spacecraft deployment in a variety of orbits of different inclinations and altitudes. These different orbit characteristics should supply a broad enough data base to permit accurate computation of the gravity field to the desired resolution.

The second approach would be to use the low-low concept mentioned earlier. In this concept, two satellites in very similar low altitude orbits track one another continuously. Proponents of this method claim a large number of advantages with respect to the high-low technique. These include the following:

- Avoidance of Ionospheric Propagation Anomalies in the Tracking Data - Since the low altitude satellites will be at altitudes of approximately 150 km, the ionospheric refraction effects will not perturb the satellite-to-satellite signal transmissions. This is occasionally a large error source and difficult to correct.

- Dynamic Range - Since the low-low satellites will be in very similar orbits the relative velocities will be very close. Thus the range rate measurement will be a small quantity. In contrast, the range rate of a low altitude satellite with respect to a geosynchronous satellite is large. Accordingly, it may be possible to measure the range rate with a much higher precision in the low-low configuration. Some initial study results suggest that a measurement precision of 10^{-4} mm/sec is achievable.

The ultimate definition of a GRAVSAT mission may include other gravity sensing techniques such as satellite radar altimeters. A substantial amount of further analysis is required to demonstrate the potential of satellite-to-satellite tracking for geodetic mapping and to define precise requirements for the capabilities of this type of mission. One advantage of using satellite-to-satellite tracking for gravity field mapping is the potential for global coverage. A second is a gravity field measurement set that is independent of the oceanographic effects that are unavoidably contained in satellite altimeter data.

CHAPTER SIX

NAVY NAVIGATION SATELLITE SYSTEM

4.6.1 Introduction

The Navy Navigation Satellite System (NNSS) was first implemented in 1964 to provide accurate position information for U.S. Navy Poseidon submarines. The system was made available to civilian users in 1967 and has, since that time, been widely applied in navigation, geodesy, and geophysics. In the following sections the Navy Navigation Satellite System is discussed in terms of the fundamental principles of operation, system organization, accuracy, applications, and future prospects. Special emphasis is placed on geodetic surveying applications and technologies.

The system is based on the fundamental physical principles of the Doppler shift and the concept of hyperbolic position determination navigation which is described in the Radio Navigation portion of Section 2.3.7. In the NNSS system the satellites transmit signals at a known frequency with data defining the position of the satellites at any time in an earth-centered coordinate system. Users at unknown locations with specially designed receiving equipment can process these signals. The user receivers measure the Doppler shift in the transmitted signal. From such measurements, along with the known satellite position information, NNSS users determine their own positions.

The evolution of this system since the mid-1960s now provides users with accuracies ranging between a few meters and a few hundred meters, depending on the quality of the user equipment, the time available to compute the navigation solution, the extent to which corrections are applied for atmospheric

phenomena, and the accuracy to which the motion of the platform can be determined. Because the system operates at frequencies of 150 and 400 MHz, navigation solutions are available at all times of the day and in all weather conditions. The Navy Navigation Satellite System has had an enormous impact on navigation and geodesy since its implementation. Evolutionary improvements in the system are expected to result in continued importance for many years to come.

4.6.2 Fundamental Principles

To understand the operation of the Navy Navigation Satellite System, consider first a simple example of a satellite in orbit transmitting a signal to a fixed receiving station. This is illustrated in Fig. 4.6-1, which shows a satellite transmitting its signal to a shipboard receiver. For purposes of illustration, three times along the satellite trajectory (t_1, t_2, t_3) are shown on the figure along with the radial distances from the satellite to the receiver (s_1, s_2, s_3). The time required for the signal to be transmitted from the satellite at time t_j to the ship is given by

$$\Delta t_j = \frac{s_j}{c} \tag{4.6-1}$$

where c is the speed of light.

The satellite transmits at a fixed frequency f_t. The frequency of the signal received at the user's receiver, f_r, is given by the following equation which defines the Doppler shift

$$f_r = f_t \left(1 + \frac{\dot{s}}{c}\right) \tag{4.6-2}$$

where $\dot{s}$ denotes the time derivative of s. Solving this equation for the range rate, $\dot{s}$, the following expression is obtained.

$$\dot{s} = \frac{c}{f_t} (f_r - f_t) \tag{4.6-3}$$

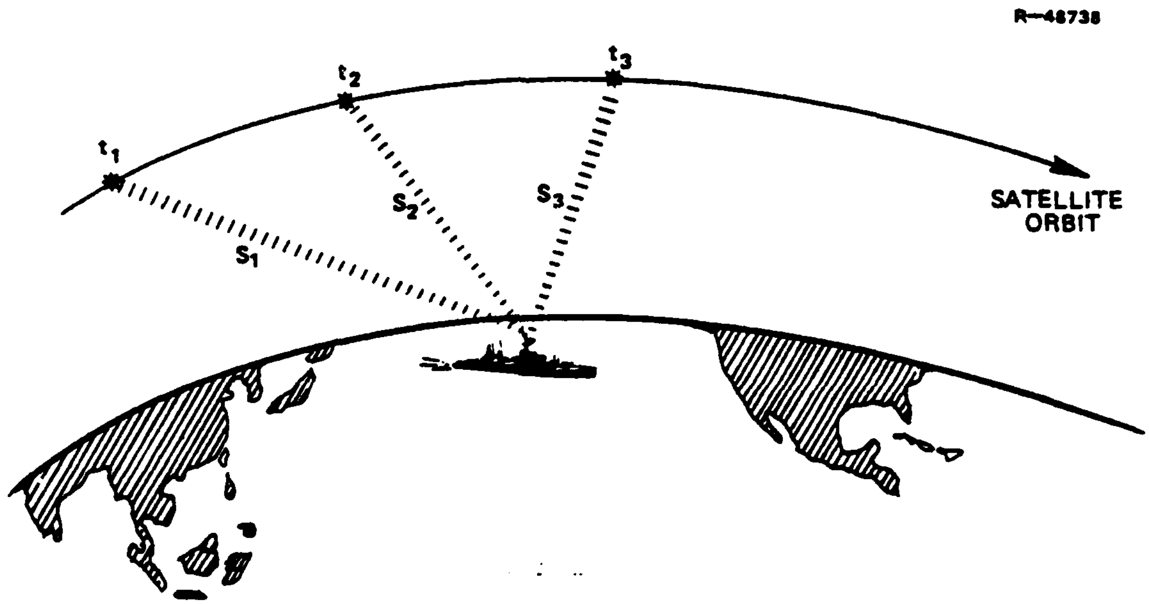


Figure 4.6-1   NNSS Transmissions from Orbit

In the actual implementation of Doppler systems, the received frequency, f_r, is compared with a stable reference frequency, f_{ref}, generated in the receiver. Doppler cycles are counted during the satellite's overhead pass, giving a Doppler count defined as

$$N_{12} = \int_{t_1+\Delta t_1}^{t_2+\Delta t_2} (f_r - f_{ref})\, dt \tag{4.6-4}$$

where

N_{12} = Doppler count

f_r = received frequency

f_{ref} = reference frequency

t_1 = time of signal transmission (start of pass)

t_2 = time of signal transmission (end of pass)

$t_1+\Delta t_1$ = time of signal reception (start of pass)

$t_2+\Delta t_2$ = time of signal reception (end of pass)

Since f_{ref} is constant,

$$N_{12} = \int_{t_1+\Delta t_1}^{t_2+\Delta t_2} f_r\, dt - f_{ref}\,(t_2-t_1) - f_{ref}\,(\Delta t_2-\Delta t_1) \tag{4.6-5}$$

Because the number of complete cycles <u>transmitted</u> during the time interval t_1 to t_2 is the same as the number of cycles <u>received</u> during the interval $(t_1+\Delta t_1)$ to $(t_2+\Delta t_2)$,

$$\int_{t_1+\Delta t_1}^{t_2+\Delta t_2} f_r\, dt = \int_{t_1}^{t_2} f_t\, dt = (t_2-t_1)\, f_t \tag{4.6-6}$$

where f_t = transmitted frequency.

Therefore, Eq. (4.6-5) becomes

$$N_{12} = (t_2-t_1)f_t - (t_2-t_1)f_{ref} - (\Delta t_2-\Delta t_1)f_{ref} \tag{4.6-7}$$

Solving for $(\Delta t_2-\Delta t_1)$,

$$(\Delta t_2 - \Delta t_1) = \frac{(f_t - f_{ref})(t_2 - t_1) - N_{12}}{f_{ref}} \tag{4.6-8}$$

Multiplication by the velocity of propagation, c, now yields the final form of the formula for the change in range:

$$\delta s = \frac{c[(\delta f)(\delta t) - N_{12}]}{f_{ref}} \tag{4.6-9}$$

where

δs = change in range during overhead pass

$\delta f = f_t - f_{ref}$

$\delta t = t_2 - t_1$

N_{12} = Doppler count

f_{ref} = reference frequency

f_t = transmitter frequency

Thus it follows that the Doppler counts provide a direct measure of the change in range between the satellite and the user receiver along the satellite trajectory. It can be shown that these changes in range, along with data defining the position of the satellite at each time along the trajectory, are sufficient to determine the user coordinates in an earth-centered coordinate system.

4.6.3 System Organization

The Navy Navigation Satellite System is made up of three principal system segments.

- The space segment, consisting of those satellites in orbit at any given time (generally 4 to 6)

- The control segment, consisting of ground tracking stations and a system control center which determines the orbit of the satellite and relays orbital information and other data to the satellites in orbit for subsequent retransmission

- The user segment, including fixed land-based users, shipboard users, and aircraft users. Since the satellites are in nearly polar orbits, they provide coverage over the entire earth, and user receiving stations have been occupied in locations at all latitudes.

The organization of the system is summarized in Fig. 4.6-2, which shows the tracking stations observing Doppler signals from the satellites at time T^1. These stations receive the Doppler data and transmit them to a computing center, which calculates future orbital parameters and time corrections used to update the orbital information on board the satellites. The injection station transmits new orbital predictions and other data to the satellites, as shown in the figure corresponding to time T^2. Finally, at time T^3, the figure shows the satellite transmitting the Doppler signal and orbital parameters to a shipboard user, who employs the data to compute the ship's latitude, longitude, and time (using an integrated receiver and computer data processing system).

The NNSS satellites are tracked from four stations located in Maine, Minnesota, California, and Hawaii. The computing and operations center for the ground tracking network is located at Point Mugu, California. The injection stations are located at Point Mugu and in Minnesota. System evalution and continued modeling activities are performed at the Applied Physics Laboratory (Johns Hopkins University) in Maryland and

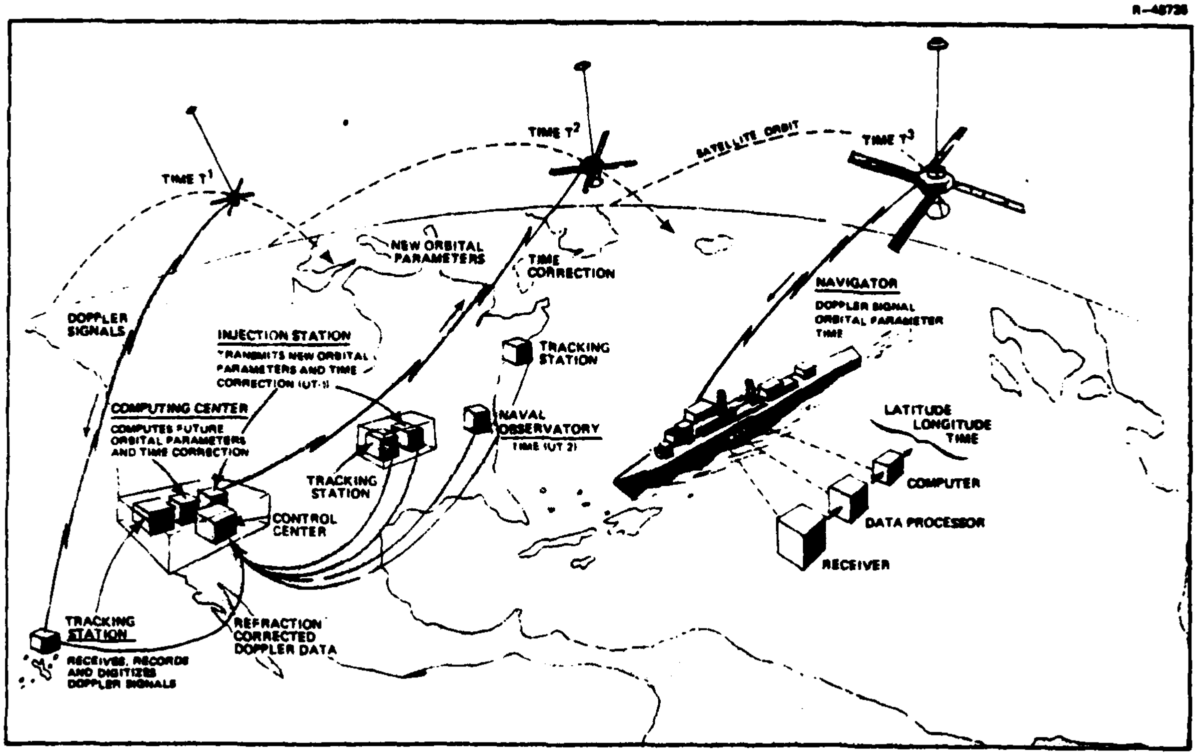


Figure 4.6-2   Navy Navigation System Concept

at the Naval Surface Weapons Center in Virginia. The locations of these stations as well as others that have been used for operating and geodetic purposes are shown in Fig. 4.6-3.

4.6.4 System Applications and Accuracy

The Navy Navigation Satellite System was originally conceived as a submarine navigation system, in which a submarine would receive data from a single satellite pass (generally lasting about 20 min) and compute its position. Continued navigation was to be done with the submarine's inertial navigation system until time for the next NNSS update.

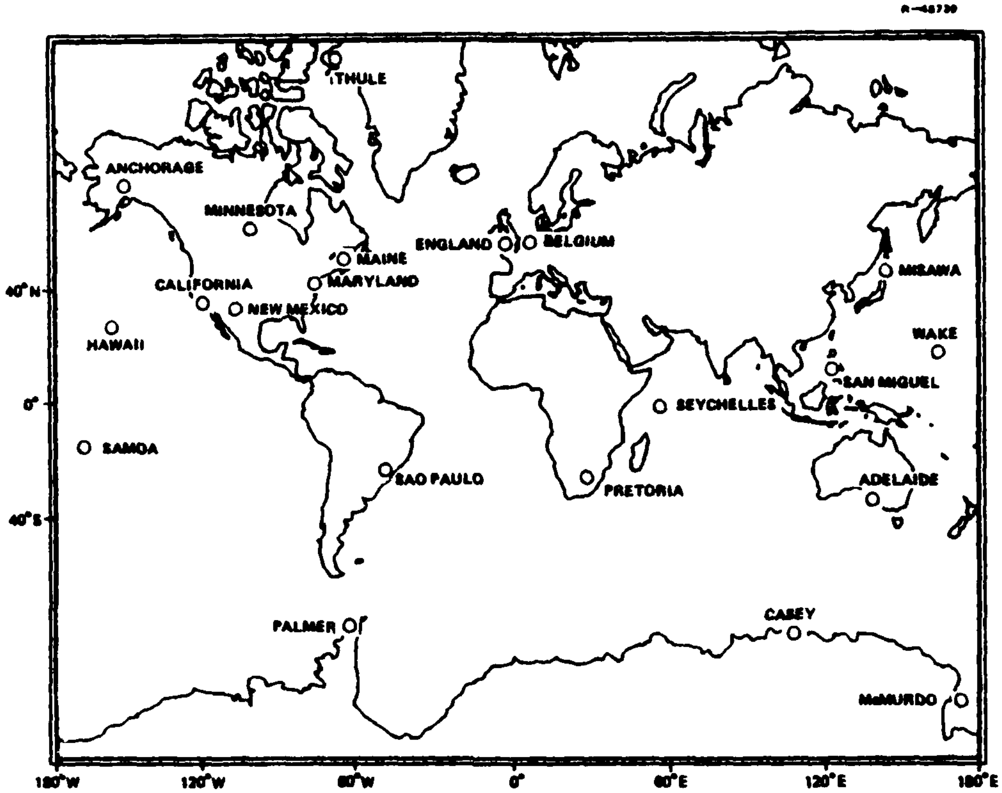


Figure 4.6-3 Locations of NNSS Operations and User Sites

However, other applications became possible as the NNSS accuracy continued to improve. The use of the NNSS for geodetic surveying is an important example. In this application, satellite passes from all of the satellites over a period of several days (or even several weeks) are collected to provide an extensive data base for computing a very accurate position. Since the accuracies currently attainable from geodetic surveying of this type are approximately 1 to 3 m, applications of the system to the estimation of polar motion and other geophysical phenomena have become possible.

With a high quality receiver system and computing capability, an RMS accuracy from a single satellite pass of 80 to 100 m is possible. The single-pass accuracy of the system is

limited by a number of phenomena. The most important of these are atmospheric refraction in both the ionosphere and the troposphere, and errors in the satellite orbit information. Some of these effects can be reduced by processing data from many satellites over a period of many days. Other effects require more careful modeling and extended data processing algorithm capabilities to reduce the errors they induce.

The effect of the ionosphere on the satellite signal is to produce a frequency shift that is not due to the motion of the satellite or the user. Since the Doppler shift is the fundamental concept of this system, any error in estimating it has serious implications. The NNSS operates at frequencies of 150 and 400 MHz. Since the ionospheric frequency shift in this range is inversely proportional to the transmitted frequency, it is possible to receive the signals at two frequencies and to reduce this effect considerably. This is an extremely important part of the NNSS operation. Without this correction it would be impossible to navigate or position with this system.

Another important source of navigation error occurs in the process of determining the satellite orbits. As mentioned earlier, the orbits are computed from data collected at four tracking stations and transmitted to a central computing facility. The computing center calculates the satellite orbit and predicts its evolution for a period of 12 to 24 hours. Since this process inevitably involves errors, the satellite orbits are inaccurate to an extent estimated to be of the order of 30 to 100 m. The orbital information transmitted to the users is called the broadcast ephemeris. To overcome the errors resulting from uncertainties in the broadcast ephemeris, a precise ephemeris is maintained for certain satellites. The data required to compute the precise ephemeris are collected

from approximately 20 Doppler stations located around the world. The precise ephemeris has the advantage of higher accuracy, but the disadvantage of requiring delays in transmission resulting from the time needed to compute these orbits. Thus, the precise ephermeris is of great importance for survey applications for which data are collected over a period of time. It is of little or no use to navigators operating in real time.

Methods for attaining higher levels of system accuracy, of importance in geodetic operations, are discussed in the next section.

4.6.5 Geodetic Receiver Operations

The Geoceiver, built by Magnavox, was first used in 1971. It was a specially designed NNSS receiver specifically for geodetic applications. Technical improvements in receiver design permit enhanced accuracy. These include improved electronics to provide greater accuracy in Doppler counts, an accurate internal clock so that the system does not have to derive its timing from the transmitted satellite signals, and provisions for processing a number of satellite passes from many different navigation satellites in order to obtain improved accuracy.

Subsequent geodetic receiver operations have made use of the precise ephemeris, described in Section 4.6.4, which provides higher accuracy. Geodetic receivers are now built by Canadian-Marconi and JMR Instruments, Inc. in addition to Magnavox. An example of the original Geoceiver is shown in Fig. 4.6-4.

Geodetic receiver operations make use of data collected from all NNSS satellites in orbit over a period of at least several days. Along with the improved receiving equipment and

R—48740

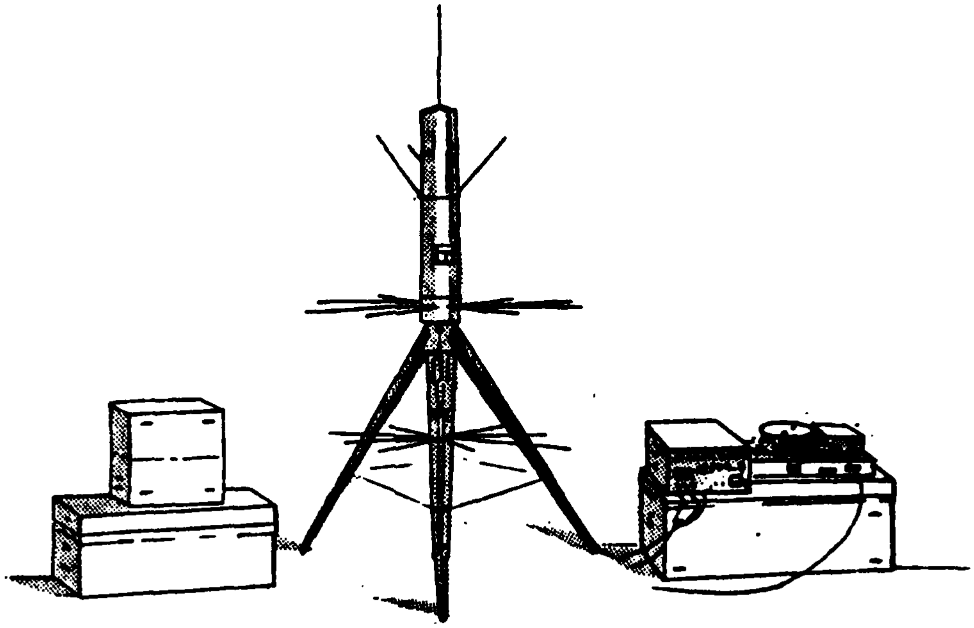


Figure 4.6-4 Geoceiver

precise ephemeris, the additional geometry from many satellite passes at various altitudes can provide a highly accurate solution for those users with sufficient computational capability to take advantage of all the data.

There are three different types of survey operations employed in geodetic receiver operations. These are the following:

- <u>Point Positioning</u> - Point positioning is similar to navigation except that it makes use of data collected from many passes in order to compute the positions with high accuracy. Generally, point

positioning accuracies on the order of 1 to 3 m are possible using current equipment.

- Translocation - In the translocation survey mode, two receivers are used simultaneously and data are collected along portions of satellite passes that are simultaneously in view at both receivers. Generally, one receiver is located at a known position, and the second receiver is located at the position to be surveyed. It is possible to compute relative coordinates of the unknown location with respect to the known location with an accuracy of approximately one meter. The translocation method makes use of the fact that some system errors (satellite orbit errors, for example) can be cancelled out in a relative solution.

- Short Arc Techniques - Short arc techniques make use of special data processing algorithms designed to reduce the impact of system errors by employing increased data processing. Relative positioning accuracies of better than one meter have been reported for point positioning using short arc techniques. For those users with sufficient computational capabilities, the short arc techniques offer excellent system performance.

4.6.6 Future System Development

Over the past fifteen years, a tremendous investment has been made in the development and operation of the NNSS. Considerable information has been collected in many locations around the world (much of which has yet to be processed) for some of the specialized applications mentioned earlier. Thus, the NNSS is expected to have a strong continuing impact on navigation and geodesy in the future. The advent of advanced satellite systems such as the NAVSTAR Global Positioning System, discussed in the next Chapter, will not alter that impact. The NNSS is expected to continue operation until at least

1990 and to continue to evolve in system capability and accuracy over that period of time.

CHAPTER 7

NAVSTAR GLOBAL POSITIONING SYSTEM

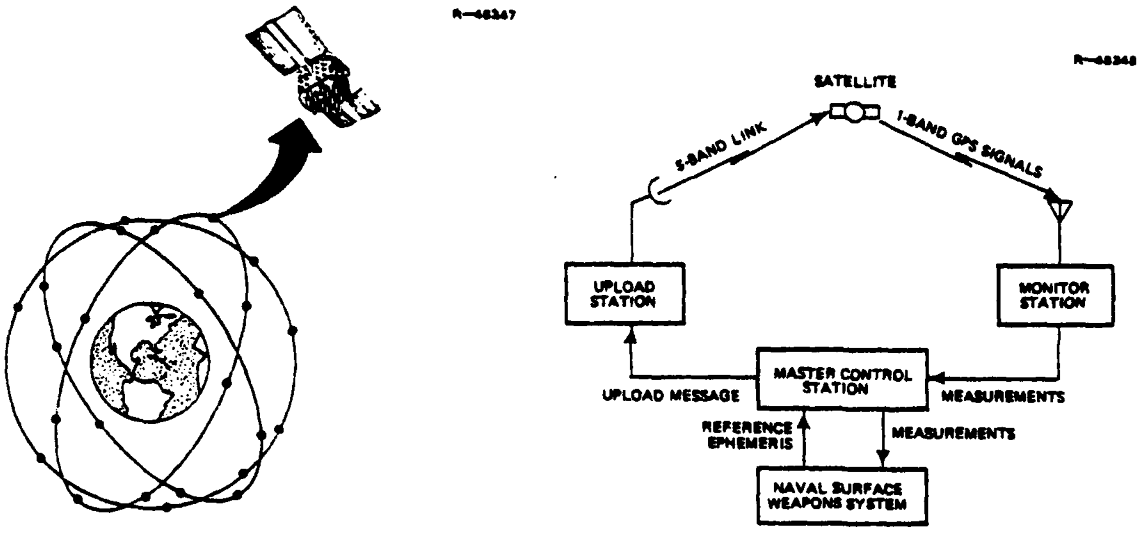
The NAVSTAR Global Positioning System (GPS) is a space-based radio navigation system scheduled to become fully operational in 1987. GPS will provide extremely accurate three-dimensional* position and velocity information to users anywhere in the world, including users in near-earth orbit. The position determinations will be based on measurements of the satellite-to-user transit time of radio frequency signals broadcast by the GPS satellite. Positioning accuracies on the order of 10 meters or better may be anticipated. The GPS system concept, how it may be used, and the expected accuracy are discussed below.

The GPS System Concept - The GPS consists of three major subsystems: the space segment, the control segment, and the user segment. The space segment includes 24 satellites operating in 12-hour orbits at an altitude of about 20,180 km. The satellites will be placed in three orbital planes (see Fig. 4.7-1) at an inclination of 55 deg and separated in longitude by 60 deg. Each orbital plane will contain eight equally-spaced satellites broadcasting navigation signals on two L-band frequencies (L_1 at 1575.42 MHz and L_2 at 1227.6 MHz). The distribution of these satellites is such that a minimum of six, and an average of eight or nine, will be in view to any earth-based or near-earth user at any given time.

The GPS radio navigation system utilizes the ρ-ρ fix-taking technique discussed in Section 2.3.7 of Unit Two. The

---

*GPS also provides accurate information in a fourth dimension -- time.



a) SPACE SEGMENT   b) CONTROL SEGMENT

Figure 4.7-1 The NAVSTAR GPS System Concept

user measures time-of-arrival (TOA) of signals received from four different satellites and, using information provided in a special navigation message, converts these TOA measurements to <u>pseudo-range</u> measurements. The term <u>pseudo-range</u> is used because each measurement contains a bias of fixed magnitude caused by uncertainties in user knowledge of GPS system time. The four measurements are required to synchronize the user receiver with GPS system time and provide an unambiguous position fix.

The pseudo-range measurement is defined as

$$\bar{r}_i = r_i + c\Delta t_{Ai} + c(\Delta t_u - \Delta t_{Si}) \qquad i=1, 2, 3, 4 \qquad (4.7\text{-}1)$$

where

$\bar{r}_i$ = pseudo-range to satellite i

r_i = true range of satellite i

c = the speed of light

Δt_{Si} = satellite i clock offset from GPS system time

Δt_u = user clock offset from GPS system time

Δt_{Ai} = propagation delays and other errors associated with satellite i

To relate these measurements to user position in earth-centered coordinates, they can be expressed in terms of four unknowns -- the user position coordinates (X, Y, Z) and user clock offset Δt_u. Equation (4.7-1) can be written in terms of these unknowns as:

$$r_i = (X_{Si} - X)^2 + (Y_{Si} - Y)^2 + (Z_{Si} - Z)^2$$

$$+ c\Delta t_{Ai} + c(\Delta t_u - \Delta t_{Si}) \qquad i=1, 2, 3, 4 \qquad (4.7\text{-}2)$$

Therefore, the navigation message broadcast from the satellite to the user must provide, as a minimum, satellite position (X_{Si}, Y_{Si}, Z_{Si}) and satellite clock offset (Δt_{Si}) in order to permit solution of Eq. 4.7-2. This information is provided to the satellite via the control segment.

The elements of the control segment are indicated in Fig. 4.7-1. The four monitor stations (located in Hawaii, Alaska, Guam, and California) are unmanned data collection centers which continuously measure pseudo-range to those GPS satellites visible to the station. The measurements are transferred at regular intervals to the Master Control Station at Vandenberg AFB in California. The data are used for generation

of reference ephemerides (satellite position and velocity) and satellite time offset estimates on a weekly basis by the Naval Surface Weapons Center in Virginia, and also to generate ephemeris updates by the Master Control Station. The ephemeris information, along with other special information used to form the satellite navigation message, is provided to these satellites as part of an upload message on a daily basis.

<u>GPS Signal Structure</u>(†) - The GPS signal consists of an L_1 and L_2 component, both of which are spread spectrum (suppressed carrier) transmissions. The signal structure was selected to permit accurate TOA measurement (approximately 10 nsec) while maximizing the rejection of external interference (background noise or jamming). The basic signal is the product of three components (see Fig. 4.7-2):

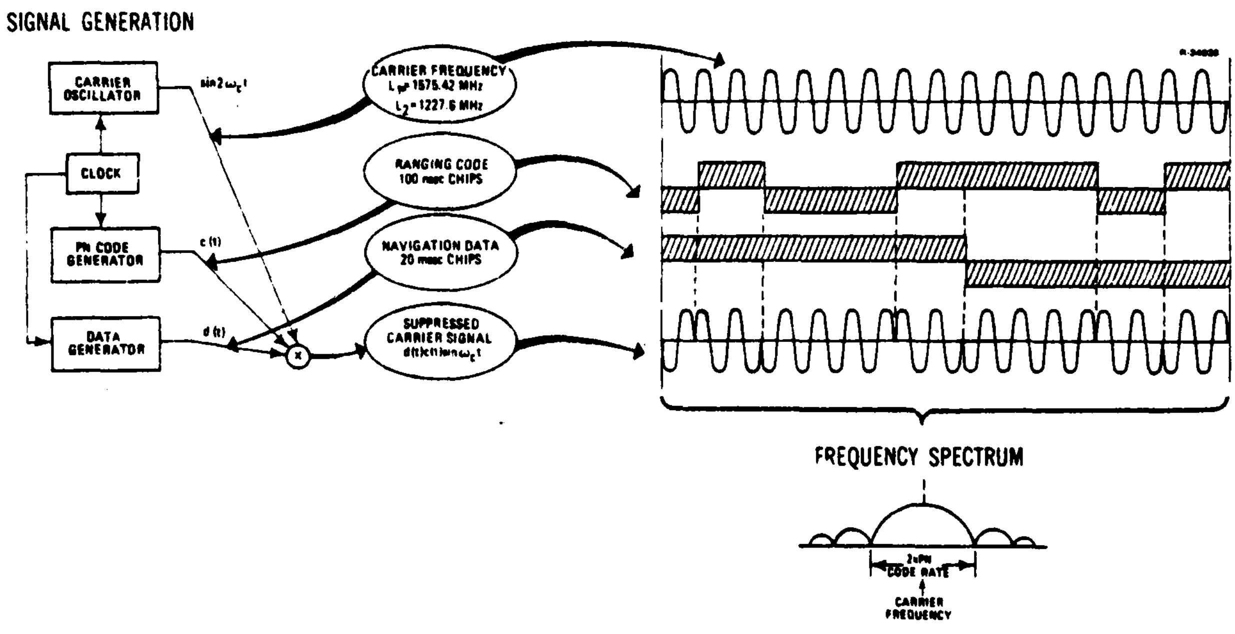


Figure 4.7-2 GPS Signal Structure

(†)This section contains material at a more advanced level than the rest of the text.

$$\text{signal} = d(t)\, c(t) \sin \omega_c t \qquad (4.7\text{-}3)$$

The carrier frequency, ω_c, is biphase modulated (BPSK)* with the satellite navigation message, d(t), and the GPS ranging code, c(t). In fact, the ranging code may be a product of two codes -- the low-accuracy C/A code and the high-accuracy P code discussed in the following paragraph. The resulting satellite transmissions have a bandwidth of approximately 20 MHz centered at the appropriate carrier frequency.

The C/A ranging code is used for initial acquisition of the GPS signal and for low accuracy navigation. Each satellite has a unique C/A code which consists of a pseudorandom noise (PRN) sequence composed of 1,023 binary chips -- each of which is approximately one microsecond long. Each satellite has a unique C/A code which repeats every millisecond on a very rigorously controlled time schedule, which is known to the user. The user generates a TOA estimate by synchronizing a stored replica of a given satellite's C/A code with the received signal. This synchronization can be accomplished with an accuracy of approximately 100 nsec, yielding a ranging (TOA) accuracy of 30 to 50 m (100 nsec). Since the C/A code repeats every millisecond there is a potential ranging ambiguity if the user does not know his position to within 370 km, but this ambiguity is readily resolved through a variety of techniques.

In contrast to the unique C/A ranging code broadcast by each GPS satellite, the satellites share a single P code,

---

*BPSK modulation consists of instantaneous ± 90 deg shifts of the carrier frequency, the sign of the shift depending on whether the binary code being added onto the signal is a "0" or a "1".

which is a PRN* sequence with a code repetition rate of 267 days. In fact, each satellite is assigned a seven day segment of the code to broadcast during a given week. The P code chip length is 100 nsec, approximately 1/10 that of the C/A code, and permits TOA measurement accuracies of better than 10 nsec. Because of the length of the P code, there is no ambiguity in the ranging measurement.

The satellite navigation message consists of a 1500 bit binary coded message modulated into the GPS signal at a 50 bit per second rate. As shown in Fig. 4.7-3, the data are broadcast in five 300 bit subframes, each of which is six seconds long. The first two words (each word is 30 bits) of each data subframe are the telemetry word (TLM) and the hand-over word (HOW). The TLM is used for system control purposes. The HOW indicates where in the seven-day P code segment the satellite is currently transmitting. Once the user has synchronized with the C/A code, decoding of the HOW is essential if synchronization with the P code is to be accomplished within a reasonable time period.

Subframes 1 through 3 of the navigation data provide the ephemerides and clock correction information necessary for precise determination of satellite position at the measurement time, as well as the satellite clock offset from GPS system time. The data subframes also contain additional information

*PRN codes are used for their unique correlation properties. If a PRN code with a chip width of T_c is multiplied by itself with a relative time difference, T_d, of less than one chip, the correlation function is proportional to $T_c - T_d$. If the time difference is greater than one chip, however, the correlation function is approximately zero. This property simplifies the signal synchronization process.

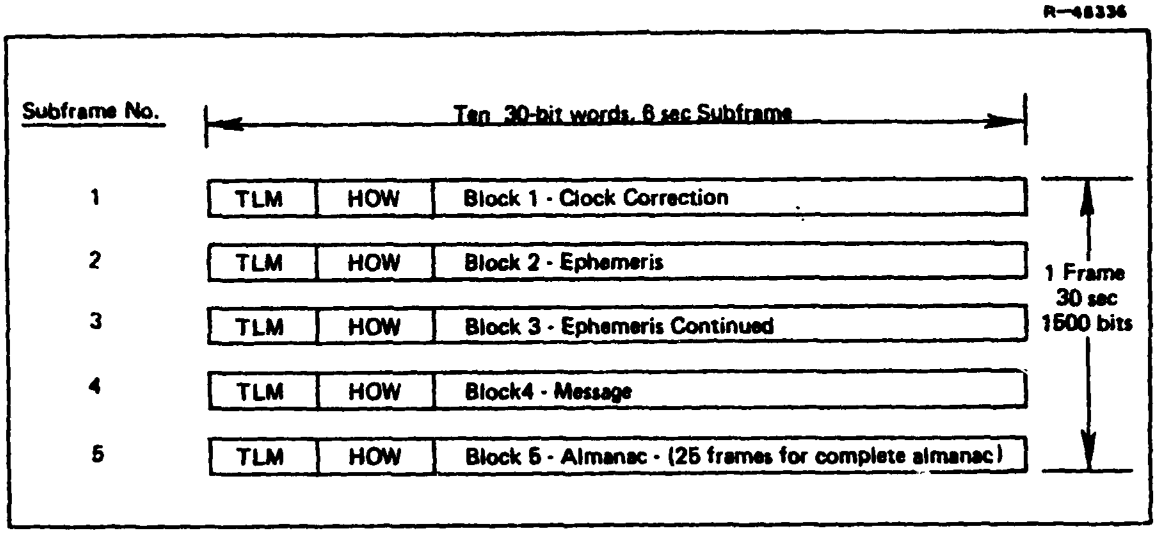


Figure 4.7-3 GPS Navigation Data Format -- Frame and Subframe Structure

such as ionospheric propagation delay model coefficients. Subframe 4 contains special message data generated by the control segment. The fifth subframe is devoted to transmission of coarse ephemerides (almanac) data for all 24 GPS satellites. Only a portion of the almanac is broadcast in each 30 sec message. Broadcast of the entire almanac takes 25 message frames, or 12.5 min.

<u>Position-Fix Accuracy</u>[†] - The position-fix accuracy attainable by GPS users is a function of a number of user-

---

(†)This section contains material at a more advanced level than the rest of the text.

specific parameters: the capability of the specific GPS user equipment, the dynamic characteristics of the user's vehicle, the availability of Inertial Navigation System (INS) data, and selection of navigation algorithms. The following discussion assumes that the user's receiver can process the high-accuracy P code and that the user either

- Has a receiver capable of simultaneously tracking four satellites,
- Is equipped with an Inertial Navigation System (INS), or
- Is stationary or slowly moving.

The achievable fix-taking accuracy is roughly comparable for these three cases.

Errors in GPS pseudo-range measurements arise from three different sources:

- Uncertainties in satellite position (ephemerides) and clock offset at the measurement time
- Signal propagation errors
- TOA measurement errors in the receiver.

A typical range error budget for P code measurements is shown in Table 4.7-1. The primary contributor to atmospheric delays is a slight reduction in propagation velocity as the GPS signal passes through the ionosphere. The combined root sum square (RSS) effect of all error sources is 3.6 to 6.3 m.

The concept of Geometric Dilution of Precision (GDOP), introduced in Section 2.3.7, is used in the following discussion. Because GPS is a four-dimensional system, GDOP in the GPS context relates to four-dimensional fix accuracy. The relationship

TABLE 4.7-1

GPS RANGE ERROR BUDGET

UNCORRECTED ERROR SOURCE	USER EQUIVALENT RANGE ERROR, RMS (Meters)
Space vehicle clock errors Ephemeris errors	1.5
Atmospheric delays	2.4-5.2
Multipath	1.2-2.7
Receiver noise and resolution Vehicle dynamics	1.5
RSS	3.6-6.3

between range measurement accuracy and position uncertainty is *given by the Position Dilution of Precision (PDOP).* *

$$\text{Position Error} = \text{PDOP} \times \text{Measurement Accuracy} \quad (4.7\text{-}4)$$

A statistical distribution of PDOP for GPS users is shown in Fig. 4.7-4 under the assumption that the user obtains measurements from the four satellites presenting the best measurement geometry**. Figure 4.7-4 indicates that 50 percent of the time, the PDOP will be 2.43 or less. With reference to Table 4.7-1, this means that 50 percent of the time the user will be

---

*PDOP is related to GDOP by the expression

$$\text{GDOP} = \sqrt{(\text{PDOP})^2 + (\text{TDOP})^2}$$

where TDOP is Time Dilution of Precision. The 50^{th} percentile value for TDOP is the number 1.21.

**Discussion of algorithms for selecting the four satellites which minimize GDOP (or PDOP) would go beyond the scope of this text. An algorithm that provides good, but not necessarily optimal, measurement geometry is one which maximizes the volume of the tetrahedron formed by the user and the four GPS satellites.

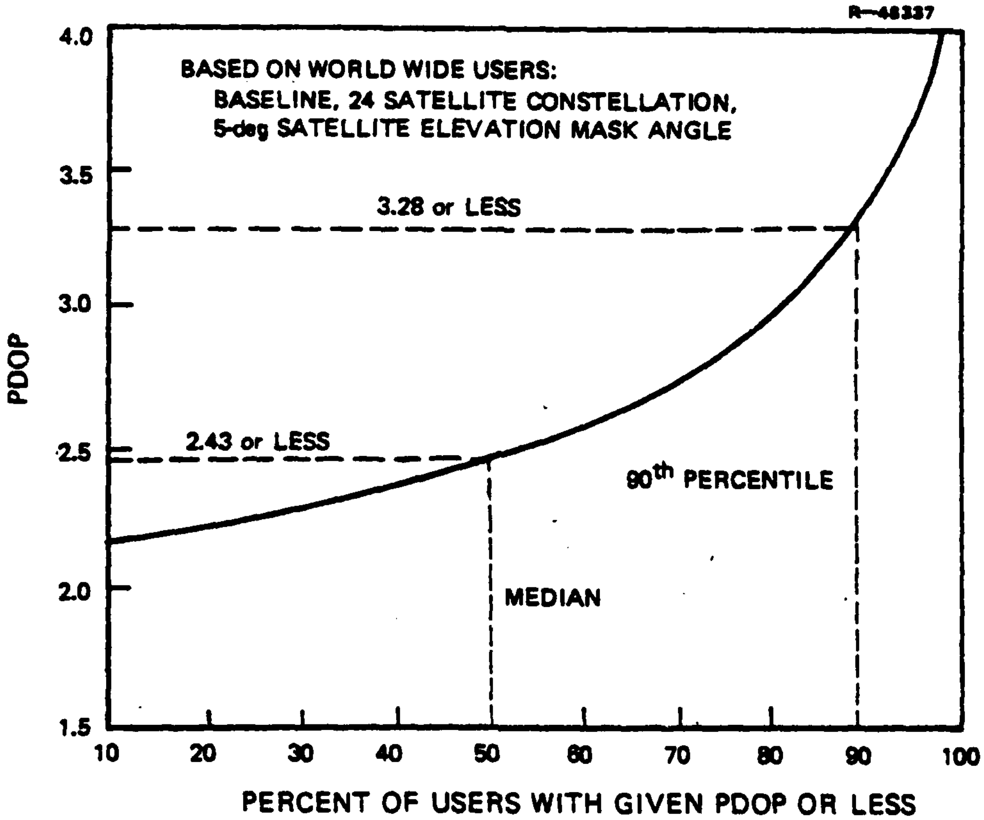


Figure 4.7-4 PDOP (Position Dilution of Precision) for GPS Users

able to obtain an RSS position-fix accuracy of between 9 and 15 m.

In addition to pseudo-range measurements, GPS provides pseudo-range-rate measurements. The systems specification is expressed in terms of an uncertainty in change of range over some given time interval, but this can be translated into typical range-rate measurement accuracies of between 0.06 and 0.015 m/sec for many users. Applying the PDOP statistics, 50 percent of the time this translates to an achievable RSS velocity-fix accuracy of 0.04 to 0.15 m/sec. Lower velocity-fix accuracy would be achieved for a moving user without an INS; higher accuracy (but at a lower measurement rate) could be attained by a moving user equipped with a highly precise INS.

CHAPTER 8
REMOTE SENSING AND LANDSAT

4.8.1 Introduction

Over the past ten years the use of remote sensing techniques (i.e., measurements of an object from a distance) has grown increasingly popular in application areas ranging from crop identification to cartography. Probably the most successful application of this technology has been associated with the NASA LANDSAT system, a sequence of three satellites, the first of which was launched in July 1972*. The mission of these satellites is to provide for the repetitive acquisition of multispectral image data of the earth's surface at a resolution level of 40 to 80 m. The satellites operate in a near-polar orbit at an altitude of approximately 920 km and circle the earth every 103 min. Any point on the earth's surface (except near the poles) is covered once every 18 days.

As shown in Fig. 4.8-1, each LANDSAT system contains a variety of support subsystems as well as two sensor systems for imaging the earth's surface -- the return-beam vidicon (RBV) camera system and the multispectral scanner (MSS). Of the two systems the MSS has been the most widely used and is described in more detail in the following sections.

---

*The first satellite was initially designated as ERTS-1 (Earth Resources Technology Satellite). This was renamed LANDSAT 1 by NASA in January 1975 following the launch of the LANDSAT 2 satellite. The LANDSAT 3 satellite was launched in March 1978. LANDSAT 2 is no longer operational and LANDSAT 3 is currently operating but encountering severe problems.

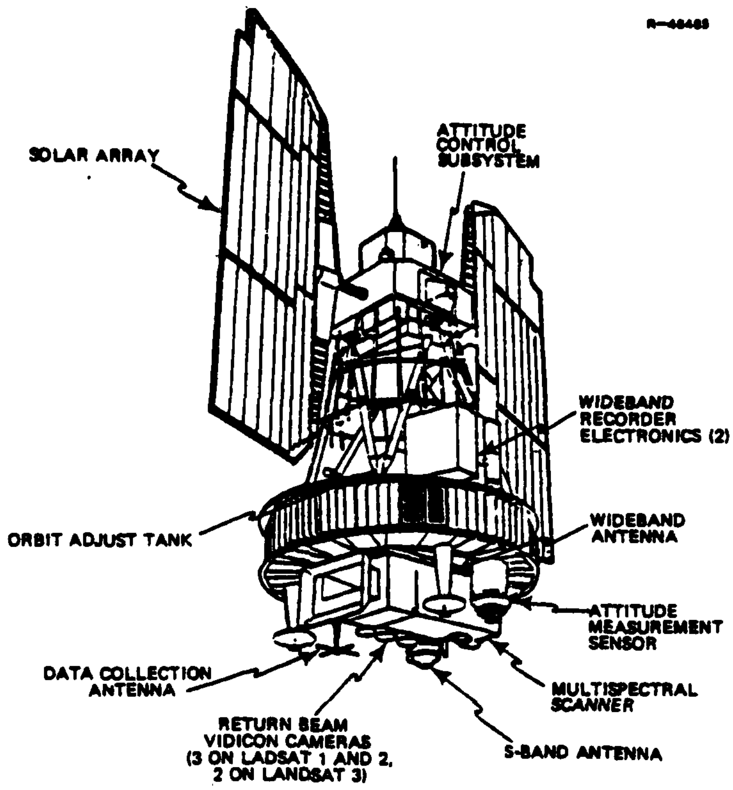


Figure 4.8-1 LANDSAT Satellite Configuration

4.8.2 Hardware Description

The LANDSAT multispectral scanner is a line scanning device which uses an oscillatory mirror to scan in a direction perpendicular to the spacecraft velocity, as shown in Fig. 4.8-2. On all the LANDSAT satellites, 24 detectors scan six lines (each 185 km long) at each of four frequency bands, as shown in Table 4.8-1. In addition, on LANDSAT 3, there are two detectors of lower resolution that provide two lines of thermal infrared data per scan. Each 185 km scan is sampled to provide about 3240 pixels (picture elements), with an effective pixel width of 57 m. The distance between image lines is 79 m.

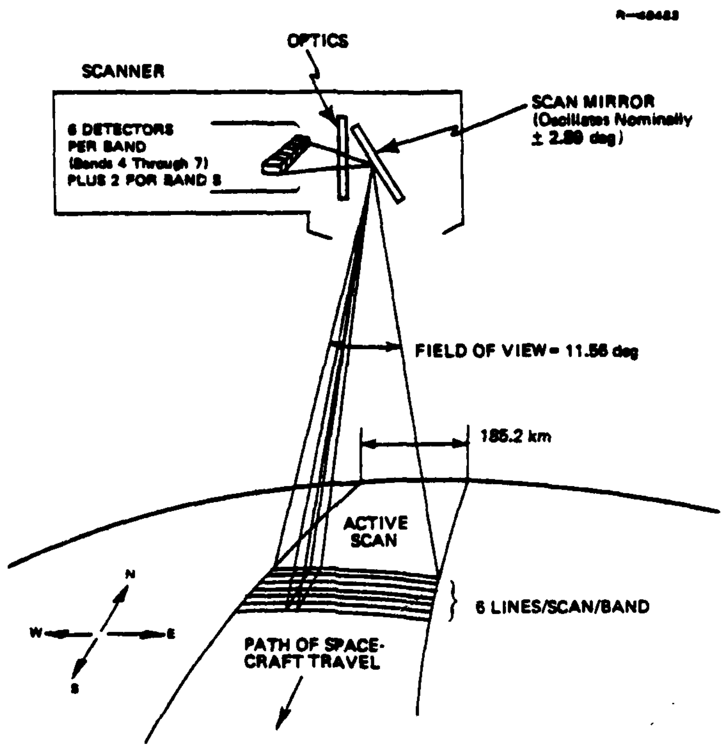


Figure 4.8-2   MSS Scanning Arrangement

TABLE 4.8-1

SPECTRAL RESPONSE FOR LANDSAT MSS BANDS

BAND*	SPECTRAL RESPONSE (MICROMETERS)
4	0.5 - 0.6
5	0.6 - 0.7
6	0.7 - 0.8
7	0.8 - 1.1
8	10.4 - 12.6 (LANDSAT 3 only)

*Bands one through three are RBV bands.

After processing, the LANDSAT scene consists of about 2160 input lines, equivalent to 170 km.

Each pixel is encoded into six-bit (one byte) digital values representing the signal amplitudes in terms of one of 64 possible discrete steps. The output from all the sensors, along with certain types of bookkeeping information (such as the starting point of each line), is multiplexed to form a 15 megabit/sec digital stream. These data are either transmitted to the ground or stored in an onboard magnetic tape recorder for transmission at a later time.

4.8.3 Practical Applications

The LANDSAT system is a powerful tool for remote sensing because a multispectral characterization is available at each point on the earth's surface. This information is provided in at least four different ranges of the electromagnetic spectrum. Not only do certain objects yield more information in some bands than others (see Table 4.8-2), but each object provides a spectral signature across the different bands. For example, vegetated areas appear dark in the blue and red visible bands, medium bright in the green visible band, bright in the near infrared, and dark (cool) in the thermal infrared bands. The signatures of various materials can be separated by the use of statistical classification techniques. This provides a method for extracting potentially vast amounts of remotely sensed data. Although these techniques have had application in a wide variety of earth science areas, the major impact has been in the fields of

- Agriculture/Forestry/Range Resources
- Land Use Survey and Mapping

TABLE 4.8-2
SPECTRAL BAND INFORMATION DESCRIPTORS

R—48487

MSS SPECTRAL BAND	7	6	5	4
AIRFIELDS			X	
AIR POLLUTION			X	X
ATMOSPHERIC SENSITIVITY				X
BURNED RANGELAND	X			
CHLOROPHYLL (Land)			X	
CHLOROPHYLL (Sea Water)	X	X		
CLOUD PENETRATION	X			
CLOUD-SNOW DIFFERENTIATION		X		
CLOUDS (Thin Cirrus)			X	X
CROP DIFFERENTIATION	X			
DEFOLIATION	X		X	
EDDIES	X		X	
FLOOD PLAINS	X			
FORESTS			X	
GEOLOGIC FEATURES	X	X		
GRASS FIRES	X			
GROWTH STATE	X			X
HAZE				X
ICE	X			X
IGNEOUS ROCKS	X	X		
IRON (Ferric)			X	X
IRRIGATED FIELDS	X			
JET CONTRAILS			X	X
LAKES	X			
LAKE EUTROPHICATIONS				X
LANDFORM FEATURES			X	
LARGE BRIDGES		X		
LARGE HORIZONTAL CONCRETE STRUCTURES			X	
LITHOLOGY			X	

R—48487a

MSS SPECTRAL BAND	7	6	5	4
MARSHES		X		
METAMORPHIC ROCK ALLUVIUM DIFFERENTIATION	X			
RIVERS	X	X		
ROADS			X	X
SERPENTINE OUTCROP	X			
SHALLOW WATER				X
SHOALS				X
SHORES	X	X		
SMALL LAKES	X			
SNOW DETECTION				X
SNOW LINES (Transient on Glacier)		X		
SNOW LINES (Forest)				X
SOIL ASSOCIATIONS		X	X	
SOIL DISCRIMINATIONS	X		X	
SOIL MOISTURE DETECTION			X	
STREAM CHANNELS		X		
STRESS			X	
SURFACE WATERS	X	X		
TECTONIC FEATURES	X	X		
TOPOGRAPHY			X	
TURBIDITY			X	X
URBAN AREAS	X		X	X
WATER BOUNDARIES	X	X		
WATER DEPTH (Bathymetry)			X	X
WATER POLLUTION			X	X
WATER SEDIMENTATION			X	X
WETLANDS	X	X		
WOODED AREAS			X	X

Note: Spectral Band descriptions are provided in Table 4.8-1.

- Mineral Resources
- Geology
- Water Resources
- Soil Mapping
- Environmental Monitoring
- Ocean Survey
- Meteorology.

The following paragraphs describe in more detail some specific applications drawn from the above categories.

Crop inventory was one of the first applications of remote sensing by satellite. With the limited global capacity for producing food and increasing world population, accurate and timely assessment of crop production is essential. The wide area coverage provided by LANDSAT, combined with rapid computer processing, has led to substantial use of this resource. Numerous applications have demonstrated that major crop species can be identified accurately from LANDSAT data. Comparisons of area estimates from LANDSAT classifications and conventional surveys agree very closely (see Table 4.8-3). In other studies, remote sensing data have been used to ascertain the extent and severity of stresses such as disease, drought, or freezing on major crops (e.g., effects of freezing on the Brazilian coffee crop). Computer-aided analysis of satellite data is proving to be a reliable tool in mapping forest cover. Applications include the location of wildlife habitats and the development of plans for timber management.

Examination of large areas (thousands of square kilometers) for potential mineral resources is another active LANDSAT

TABLE 4.8-3

LANDSAT AND U.S. DEPARTMENT OF AGRICULTURE (USDA) CROP AREA ESTIMATES

PERCENT OF TOTAL AREA		
CROP	USDA	LANDSAT
Corn	40.2	39.6
Soybeans	18.0	17.8
Other	41.8	42.6

application. LANDSAT MSS data are valuable for detecting and mapping regional fracture systems and detecting surface characteristics associated with mineral deposits. Expensive techniques such as ground prospecting are avoided and need not be used except as part of follow-up investigation in the particular regions of interest identified by the LANDSAT data. Land-use inventories, which involve the classification of areas by use (e.g., transportation, urban, water and wetlands, forest, agricultural, etc.), are important for identifying sources of pollution, developing zoning and planning information, and in cartographic applications.

LANDSAT data have also been used for oceanic surveys. In a bathymetric application, MSS data are used in clear water to measure depths up to 20 m with ±10 percent accuracy and up to 40 m with ±20 percent accuracy. Monitoring the location and movement of sea ice for the purpose of identifying navigation hazards has also been demonstrated. Biologically rich ocean areas are located by analysis of surface water details obtained from LANDSAT data.

Although illustrative of the types of applications where LANDSAT data have been exploited profitably, the foregoing discussion touches on just a small portion of the experimentation currently being done. The reader interested in further details is referred to the LANDSAT Data Users Handbook, published by NASA, and to proceedings of numerous conferences and symposiums.

4.8.4 Data Transmission and Postprocessing

The overall LANDSAT system is shown in Fig. 4.8-3. Satellite data and orbital parameters are processed by NASA at the Goddard Space Flight Center (GSFC) in Maryland and by the U.S. Geological Survey (USGS) at the Earth Resources Observation System (EROS) Data Center in South Dakota. The EROS Data Center then distributes the final products to the user community in the form of photographic film and digital tapes.

NASA and USGS have introduced new procedures for processing of LANDSAT data using two digital processing systems called the Image Processing Facility (IPF) at GSFC, and the EROS Data Center Image Processing System (EDIPS) in South Dakota. The IPF provides the first level of processing, creating high-density digital tapes which are sent to the EDIPS where digital and photographic products are created for distribution to the final users. Figure 4.8-4 illustrates the data flow and products available at each step.

The IPF at Goddard uses the sensor data tapes from the NASA data receiving stations, the GSFC-computed spacecraft emphemeris, spacecraft performance telemetry, and a library of ground control points to produce a high-density digital product tape (HDT-P). The processing of HDT-Ps involves the radiometric restoration of the sensor data recorded on the station tapes

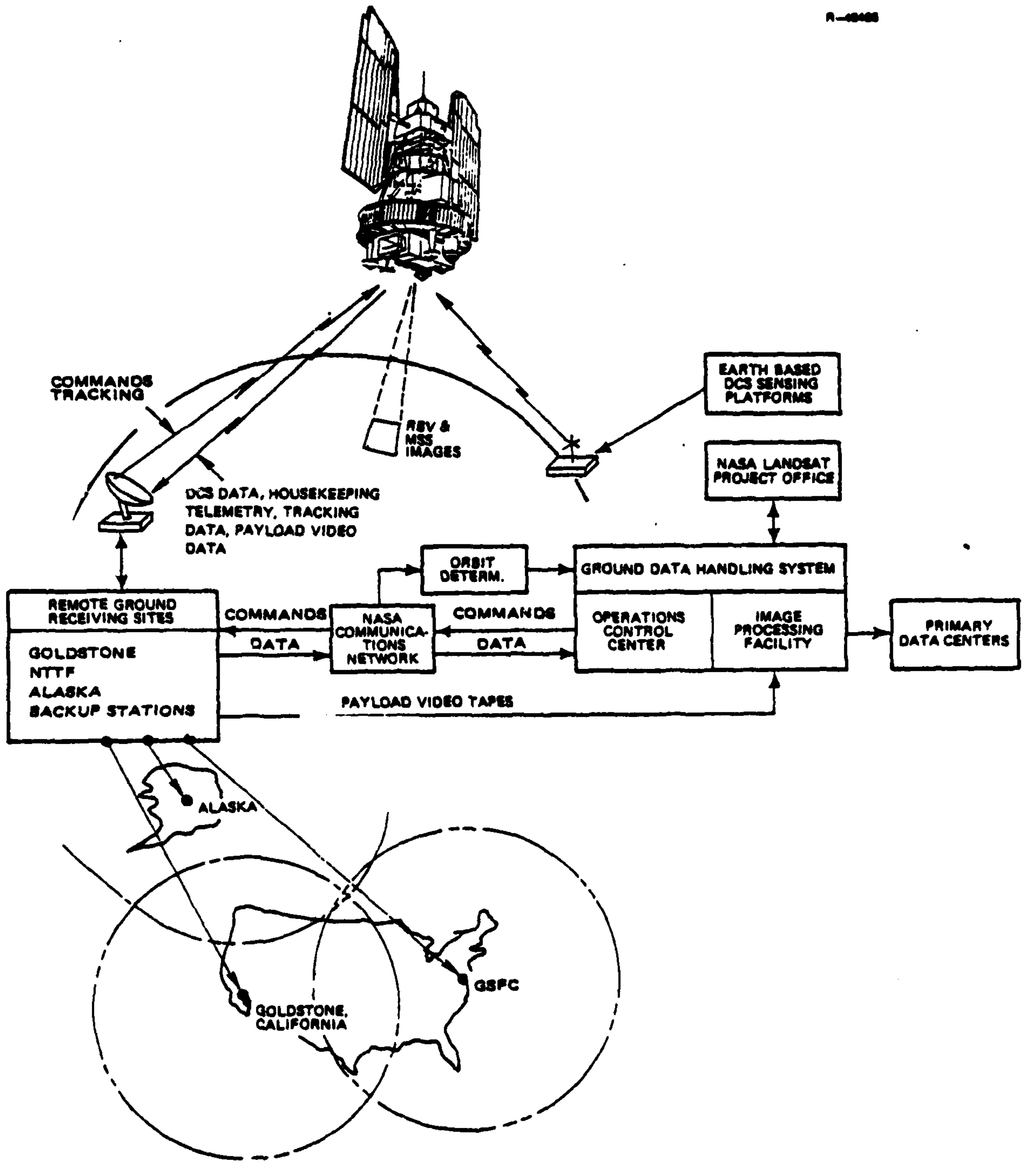
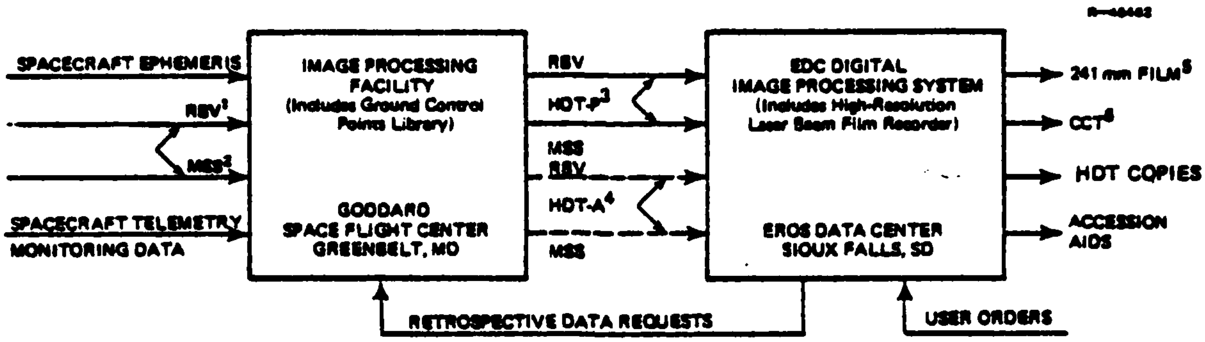


Figure 4.8-3 Overall LANDSAT System



NOTES:

1) Two 236 mm panochromatic (0.505-0.750 micrometer) return-beam vidicon (RBV) cameras – Landsat-C.

2) Five-band multispectral scanner (MSS-0.5-0.6, 0.6-0.7, 0.7-0.8, 0.8-1.1, and 10.4-12.6 micrometer)– Landsat-C.

3) Fully corrected high-density digital tape (DT): Space Oblique Mercator (SOM) Projection cubic re-sampled standard-Universal Transverse Mercator or Polar Stereographic projection and nearest neighbor optional via retrospective data request.

4) Radiometrically corrected high-density digital tape (HDT): no geometric corrections, no options; available by retrospective data request.

5) Third generation positive Space Oblique Mercator (SOM) projection, cubic resampling-standard-enhancements and other photographic derivatives optional. No photographic products from partially corrected high-density digital tapes.

6) Computer-Compatible tape. RBV available in subscene sequential format from either HDT-P or HDT-A, in 800 or 1600 bit/in mode available in band sequential or band interleaved format from both HDT-P and HDT-A.

Figure 4.8-4 Data Flow through NASA-Goddard Space Flight Center Image Processing Facility and EROS Data Center (USGS)

to correct for detector gain and offset, the computation and application of geometric corrections, and reformatting of the data. The geometric correction depends upon spacecraft attitude and position, detector geometry, mirror scan velocity, earth rotation, image projection, and the correlation of detectable ground control points with accurately known locations.

An important function of the geometric correction process is to apply cartographic projection transformations (review Section 1.2.6, Unit One) so that the resulting images will be compatible with existing maps. Two types of Mercator projection -- Universal Transverse Mercator (UTM) and Space Oblique Mercator (SOM) -- are standard for regions within 65 deg of the equator, while the polar stereographic projection is used at higher latitudes.

The HDT-P data are resampled with a cubic convolution resampling algorithm, except in those cases where a user orders data with the optional nearest-neighbor resampling algorithm. If a data user desires uncorrected data, a so-called HDT-A* is produced. The data have undergone radiometric restoration (gain and offset), but no geometric corrections or resampling. These HDTs are then transmitted to the EROS Data Center for further processing.

The EROS Data Center digital image processing system transforms the HDT-P data into (1) latent film imagery or (2) digital magnetic tape products. The processing system consists of a computer, an array processor, two high-density tape recorders, and a high-resolution laser-beam film recorder. Normally, EDIPS will process only HDT-Ps. HDT-As (archival) will be produced by IPF and processed by EDIPS only upon special request.

The major processing capability at EDIPS includes:

- Generation of brightness-value distribution data, including a histogram portraying the distribution
- Contrast enhancement based on data provided by the brightness-value distribution

---

*-A indicates archival.

- Haze removal based on data provided by the brightness-value distribution

- High-frequency edge enhancement or restoration

- Production of two separate output products: film and digital

- Selection of specified images from an HDT.

Haze removal and contrast enhancement are ordinarily done during EDIPS processing; however, these functions are selectable and may be omitted if desired. Edge enhancement (or high-frequency restoration) is performed only when specifically ordered.

The EDIPS prepares all HDT imagery in a 241 mm format with the EDIPS high-resolution film recorder. This laser-beam film recorder produces first-generation negatives or positives. The EROS Data Center uses negatives for working masters, and delivers second-generation positives to the data user. Computer-compatible tape data from the HDTs is formatted and recorded by EDIPS for delivery to the user.

All of these operations are really of a preprocessing nature before the actual information extraction process is begun. Depending on the application, further preprocessing may be done to reduce noise, change magnification, modify contrast, or prepare a mosaic of multiple passes. Then various visual or statistical techniques are used to cluster or classify the data according to desired categories and/or perform pattern recognition techniques such as change detection, object identification, and map update. Finally, the results are usually displayed on a monitor screen, scanned onto film, or tabulated.

4.8.5 Future Directions

Research performed in the 1960s led to the new technology of remote sensing and the launching of the first satellite intended for this purpose. Since then, two more LANDSAT satellites have been launched, plans for at least two additional LANDSAT satellites are proceeding, and an operational system of earth resource satellites is under consideration. The significant trends have been

- An increased number of spectral bands and higher resolution, providing more detailed and accurate classifications of earth surface materials
- Real-time transmission of data through relay satellites (NASA Tracking and Data Relay Satellite)
- More use of ancillary data from a variety of sources including spatial and temporal sensors
- More sophisticated processing algorithms and hardware systems
- Increased understanding of earth features and their spectral responses.

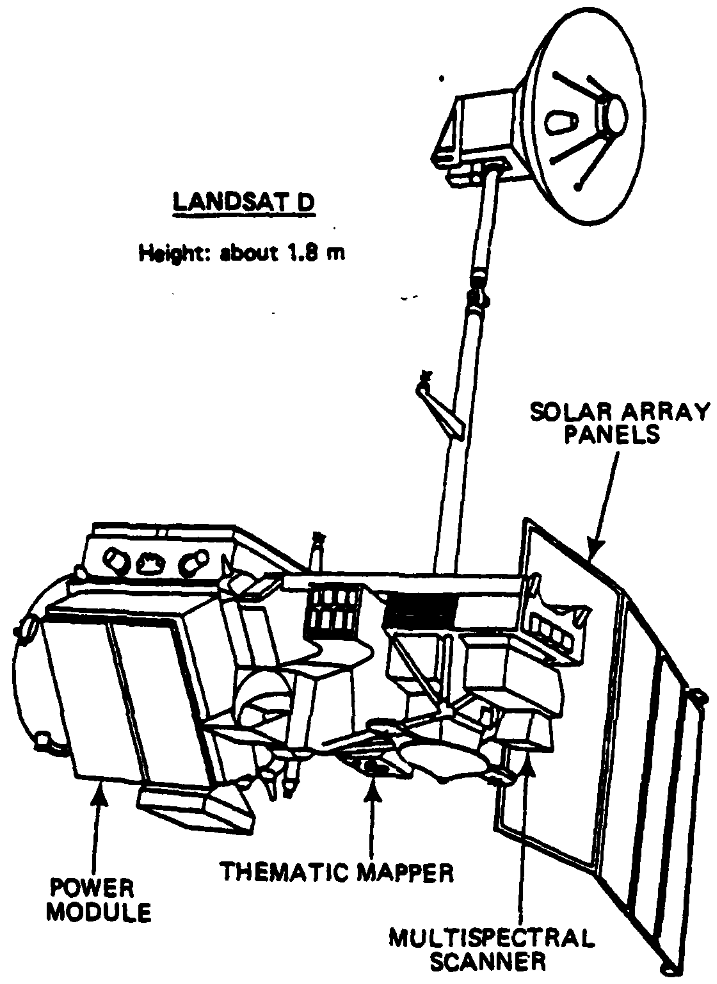
A number of these trends are evident in the next satellite planned in the LANDSAT series, LANDSAT D (which, after successful launch, will be redesignated LANDSAT 4). It will serve as the platform for a multispectral scanner, similar to that currently in operation aboard LANDSAT 3, and a new thematic mapper. Launch is planned for the fourth quarter of 1981. An identical satellite, LANDSAT D', is scheduled for launch about six months later.

LANDSAT D will have a nominal orbital altitude of 705 km and will maintain a 16-day cycle of repetitive coverage.

The two onboard sensors will provide ground coverage of about 185 × 170 km per scene. The multispectral scanner will sense data in the same four bands as the present multispectral scanner on LANDSAT 3, with the same instantaneous field of view (80 m). The thematic mapper, a line-scanning device also, will operate over 7 bands and have an instantaneous field of view of 30 m (see Fig. 4.8-5). This is a significant increase in both spatial and spectral resolution and will test the capability of the thematic mapper to provide improved information for earth resources management.

A new ground processing system is being implemented at NASA/Goddard for LANDSAT D data. The system will receive sensor data via the new Tracking Data and Relay Satellite System and will produce high-density tapes, computer-compatible tapes, and film of the data within 48 hours. Approximately 200 multispectral scanner scenes per day will be converted to geometrically-uncorrected high-density tapes in the same format as the HDT-A of LANDSAT 3. The geometrically corrected output pixel size will remain 57 m square. Each day, about 50 scenes from the thematic mapper will be geometrically corrected and converted to high-density tapes. NASA/Goddard will then generate 241 mm film from these tapes for shipment to the EROS Data Center. The geometrically corrected output pixel size of thematic mapper data will be 28.5 m square. A new digital image processing system for producing digital thematic products is currently under consideration by NASA and the EROS Data Center.

R—48479



SPECTRAL COVERAGE OF THEMATIC MAPPER

BAND	MICROMETERS
1	0.45 - 0.52
2	0.52 - 0.60
3	0.63 - 0.69
4	0.76 - 0.90
5	1.55 - 1.75
6	10.40 - 12.50
7	2.08 - 2.35

Figure 4.8-5 LANDSAT D Satellite System and Thematic Mapper Spectral Bands

UNIT FOUR
REVIEW EXERCISES

Chapter Two

1. Explain what is meant by the term telemetry or telemetry data.

2. Assume that a spacecraft has the form of a circular cylinder 1 m in diameter and 100 m long. The spacecraft is aligned with the axis of the cylinder pointing toward the center of the earth, and is in a circular orbit at a height of 600 km. Compute the difference in gravitational attraction between the two ends of the cylinder.

3. If an earth satellite has no internal heat sources, will it eventually cool to a temperature of absolute zero?

Chapter Three

4. Assume a satellite in a retrograde, nearly polar, circular orbit with an inclination of 99 deg. The height of the satellite at its equatorial crossings is 890 km. Compute the daily change in Ω, the right ascension of the ascending node.

5. For the satellite described in the preceding exercise, what is the annual nodal change? Why is such a satellite called sun-synchronous? Why are sun-synchronous satellites important for photographic and remote-sensing applications?

6. Could a sun-synchronous system be designed involving a satellite in a direct, rather than retrograde, orbit?

Chapter Four

7. What are some of the means of attitude determination used by satellites?

8. Could a star tracker be used to track planets instead of stars? Which planets would be suitable? What would be the advantages and disadvantages of tracking a planet instead of a star?

Chapter Five

9. Distinguish between active and passive systems for tracking satellites and determining their orbits.

10. Discuss the similarities and differences between laser and radar systems.

11. Reference is made, in this and other chapters, to radar devices operating at C-band, L-band, S-band, etc. To what do these letters refer?

12. The orbital inclinations of the GEOS-3 and SEASAT-1 satellites are given in the text as 115 deg and 108 deg, respectively. What is the meaning of an inclination greater than 90 deg?

13. Use Eq. (4.5-1) to estimate the velocity of an ocean current crossed at right angles by the subtrack of a satellite equipped with a radar altimeter, given that the altimeter detected a change in ocean height of 1 m over a 300 km current width. Assume that the crossing occurred at latitude 30 deg South.

14. Explain the meaning of the word ephemeris.

15. Using the data given in Table 4.5-1, calculate the orbital eccentricity for each of the three satellite types listed.

Chapter Six

16. If a satellite is transmitting at a frequency held precisely at 150 MHz, and is approaching an observer at 100 m/sec, find the frequency of the signal received by the observer.

17. How accurately must a ground observer measure the frequency of the signal received from a satellite in order to determine the radial velocity to within one mm/sec? Assume that the satellite transmitter frequency is 400 MHz.

18. During a tracking interval of 10 sec, the frequency of the signal received from a satellite increases linearly from

$$f_r(0) = f_{ref} = 150 \text{ Mhz}$$

to

$$f_r(10) = f_{ref} + 50 \text{ Hz}$$

Find the total Doppler count over this interval.

19. Assume that a ground receiver measures a Doppler count of 250 cycles during a tracking interval of 10 sec. The receiver's stabilized reference frequency is exactly 150 MHz, while the satellite's transmission frequency is known to be 149.998 MHz. Compute the change in range (from satellite to receiver) during the tracking interval.

20. Discuss the accuracy requirements for measured Doppler count in terms of desired accuracy in the determination of change in range.

21. Why does the NNSS use the dual-frequency (150 and 400 MHz) mode of operation?

Chapter Seven

22. Why is GPS sometimes referred to as a four-dimensional positioning system?

23. Explain the meaning of the term pseudo-range, as used in the context of GPS.

24. Would the predicted accuracy of the fully operational GPS be adequate for use by military aircraft as a precision landing system under conditions of zero ceiling and visibility?

Chapter Eight

25. Why are remote-sensing satellites like LANDSAT placed in nearly polar orbits?

26. Which agencies of the United States government are primarily involved in the processing and dissemination of LANDSAT data?

27. Identify the three map projections used for the presentation of LANDSAT data in map-compatible form.

UNIT FOUR

READING LIST

National Geodetic Satellite Program, National Aeronautics and Space Administration, Washington, 1977.

Leondes, C.T. (ed), Guidance and Control of Aerospace Vehicles, McGraw-Hill, New York, 1963.

Wertz, J.R. (ed), Spacecraft Attitude Determination and Control, D. Reidel Publishing Company, Boston, 1978.

Chapter Three

Kaula, W.M., Theory of Satellite Geodesy, Blaisdell Publishing Company, Waltham, Mass., 1966.

Herrick, S., Astrodynamics, Van Nostrand/Reinhold, New York, Vol. 1, 1971, Vol. 2, 1972.

Roy, A.E., Orbital Motion, Wiley (Halsted Press), New York, 1978.

Chapter Eight

LANDSAT Data Users Handbook, (Revised Edition), U.S. Geological Survey, Washington, 1979.

Sabins, F.F., Remote Sensing: Principles and Interpretation, W.H. Freeman, San Francisco, 1978.